CHANDRA X-RAY IMAGING OF THE INTERACTING STARBURST GALAXY SYSTEM NGC 7714/7715: TIDAL ULTRALUMINOUS X-RAY SOURCES, EMERGENT WIND, AND RESOLVED H II REGIONS

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ABSTRACT

We present high spatial resolution X-ray imaging data for the interacting galaxy pair NGC 7714/7715 (Arp 284) from the Chandra X-ray telescope. In addition to the unresolved starburst nucleus, a variable point source with \( L_X \approx 10^{40} \) ergs s\(^{-1}\) was detected 1.5 (270 pc) to the northwest of the nucleus, coincident with a blue, extremely optically luminous \( M_B \approx -14.1 \) point source on Hubble Space Telescope images. Eleven other candidate point-like ultraluminous X-ray sources (ULXs) were also detected in the vicinity of NGC 7714/7715, two of which exceed \( 10^{40} \) ergs s\(^{-1}\). Ten of these appear to be associated with interaction-induced features, but only two are associated with star formation regions. We also found diffuse emission with \( L_X \approx 3 \times 10^{40} \) ergs s\(^{-1}\) extending 11\(^{\prime}\) (1.9 kpc) to the north of the nucleus. Its spectrum can be fitted with either a two-temperature MEKAL function \( (kT = 0.59^{+0.05}_{-0.06} \text{ and } 8^{+10}_{-3} \text{ keV}) \) or a 0.6 keV MEKAL function plus a power law \( (\Gamma = 1.8 \pm 0.2) \). The hard component may be due to high-mass X-ray binaries (HMXBs) with possible contributions from inverse Compton radiation, while the soft component is likely from a superwind. Superbubble models imply an expansion age of \( \approx 15 \) Myr, supporting previous assertions of an intermediate-age nuclear stellar population in addition to a 5 Myr starburst. We also detected extended X-ray emission associated with four extranuclear H II region complexes. The emission from these H II regions and the nuclear starburst could be due to either an enhanced population of HMXBs relative to Local Group galactic averages or to diffuse gas heated by winds from supernovae, if the X-ray production efficiency \( L_X/L_{\text{mech}} \) is high (\( \approx 5\% \)). To estimate \( L_X/L_{\text{mech}} \), we collected published data for well-studied H II regions and superbubbles in nearby galaxies. For H II regions with ages less than 3.5 Myr, the median \( L_X/L_{\text{mech}} \approx 0.02\% \), while for older star formation regions, \( L_X/L_{\text{mech}} \approx 0.2\% - 7\% \). Thus, it is possible that gas heating by supernovae may be sufficient to account for the observed X-rays from these H II regions. In galaxies much more distant than NGC 7714, for example, the Cartwheel galaxy, H II region complexes similar to those in NGC 7714 will be unresolved by Chandra and will mimic ULXs. No X-ray emission was detected from the Type Ib supernova SN 1999dn, with an upper limit of \( \approx 2 \times 10^{38} \) ergs s\(^{-1}\). Keywords: galaxies: individual (NGC 7714, NGC 7715) — galaxies: interactions — galaxies: starburst

1. INTRODUCTION

1.1. X-Ray Emission from Starburst Galaxies

The X-ray properties of starburst galaxies tend to scale with star formation activity (Fabbiano 1989; Read & Ponman 2001; Ranalli et al. 2003); however, this X-ray emission is still not completely understood. With the high spatial resolution of the Chandra telescope, we can now separate point sources from the diffuse emission in starburst galaxies, allowing these two components to be studied with unprecedented detail. Chandra observations have provided new information about the distribution, temperature, and metallicity of hot X-ray-emitting gas in starbursts, and, in particular about “superwinds”: high-velocity large-scale outflows from the nuclear regions of starbursts (e.g., Strickland et al. 2000, 2002, 2004a, 2004b; Martin et al. 2002; Rasmussen et al. 2004). Chandra images have also revealed extended emission associated with extranuclear star formation regions in both starburst and spiral galaxies (Fabbiano et al. 2003; Zezas et al. 2003; Kuntz et al. 2003; Tyler et al. 2004); however, this phenomenon is not well quantified.

Chandra observations have also shown that star-forming galaxies often contain numerous “ultraluminous” X-ray (ULX) point sources \( L_X \geq 10^{39} \) L\(_{\odot}\); Fabbiano et al. 2001; Roberts et al. 2002; Lira et al. 2002; Zezas & Fabbiano 2002; Zezas et al. 2003; Read 2003; Smith et al. 2003). The nature of these sources is still unclear. One suggestion is that they are “intermediate-mass” \( (100-\)10\(^5\) M\(_{\odot}\) ) black holes (Colbert & Mushotzky 1999; Krongold 2004); alternatively, they may be stellar mass black holes in X-ray binaries that are beamed (King et al. 2001; Körding et al. 2002) or have super-Eddington accretion rates (Begelman 2002). More information about such sources, particularly information about environment and possible optical counterparts, is needed to distinguish between these scenarios.

In order to study hot gas, superwinds, and ULXs in starburst galaxies, we require systems close enough that their X-ray emission can be resolved by the Chandra telescope. Targeting starburst galaxies undergoing an interaction with another galaxy can
be especially useful if detailed dynamical modeling of the interaction is available. For only a few starburst systems are sufficient data available for such a comparison. One such system is the peculiar galaxy pair NGC 7714/7715 (Arp 284), which contains one of the best studied examples of an interaction-induced starburst. NGC 7714 is relatively nearby, at only 37 Mpc

The unusual morphology of NGC 7714/7715 provides strong constraints on its dynamical history, making possible a detailed comparison of the parameters of its starburst and the parameters of its interaction. NGC 7714 has a partial ring, two tails to the west and another to the east (Fig. 1; from Arp 1966). The presence of both a partial ring and tails suggest an off-center collision (Smith & Wallin 1992). In 21 cm H i maps (Fig. 2; from Smith et al. 1997), a gaseous counterpart to the western stellar tail makes a full loop back to the bridge. This loop implies a prograde encounter relative to NGC 7714 (Struck & Smith 2003). This bridge is rich in H i ($M_{HI} \approx 1.5 \times 10^9 \, M_\odot$; Smith et al. 1997), with luminous H ii regions (Bernlohr 1993; González-Delgado et al. 1995; Smith et al. 1997). The gas and young stars in the bridge are offset to the north of an older stellar bridge. Star formation is also seen in an arc northwest of the nucleus, southeast of the nucleus, and in the inner western tail (Bernlohr 1993; González-Delgado et al. 1995; Smith et al. 1997). Molecular gas has been detected in the disk of NGC 7714, but not elsewhere (Smith & Struck 2001).

Using these constraints as well as kinematical information, we have constructed a detailed hydrodynamic model of this system (Struck & Smith 2003). Our model predicts significant mass transfer from NGC 7715 to NGC 7714, fueling the central starburst and creating the inner southwestern tail. The star formation history of NGC 7714 predicted by our dynamical model is consistent with that inferred from spectral synthesis models. In the model, however, the predicted gas velocity dispersion in the center of NGC 7714 is significantly less than in the real H i map, implying contributions from a superwind. This is confirmed by ultraviolet spectroscopy with the Far-Ultraviolet Spectroscopic Explorer, which shows a $\approx 900$ km s$^{-1}$ wind (Keel et al. 2004).

With the ROSAT X-ray satellite, Papaderos & Fricke (1998) found extended X-ray emission near the center of NGC 7714 and concluded that this was due to hot gas heated by a nuclear starburst. Alternatively, the X-ray emission from the NGC 7714 nucleus may be due to X-ray binaries (Ward 1988). Papaderos & Fricke (1998) also detected a second X-ray source 20$''$ east of the nucleus, which they suggested was due to hot gas heated by either infall of gas from the bridge or a nuclear superwind. More recent observations with the XMM-Newton X-ray telescope by Soria & Motch (2004) showed that this eastern source is variable and pointlike, indicating that it is a possible ULX rather than hot gas. Soria & Motch (2004) also found that the XMM-Newton spectrum of the central region had two components, a nonvariable thermal plasma and a variable power law, suggesting a possible obscured active galactic nucleus (AGN). In contrast, Spitzer infrared spectroscopy shows no evidence for an obscured AGN (Brandl et al. 2004).

2. OBSERVATIONS AND DATA REDUCTION

To study the X-ray emission from NGC 7714/7715 at higher spatial resolution than previous observations, we observed NGC 7714/7715 for 60 ks on 2004 January 24 with the Advanced CCD Imaging Spectrometer (ACIS) backside-illuminated CCD chip S3 on the Chandra X-ray telescope (Weisskopf et al. 2002). This CCD has $1024 \times 1024 \, 0.492$ pixels. To minimize pileup, we only read out 640 chip rows, giving an observed field of view of 5.2 $\times$ 8.4. This covers the entire NGC 7714/7715 system, except for the end of the eastern NGC 7715 tail. The CCD temperature was $-120^\circ$, the frame time was 2.1 s, and the events were telescoped in FAINT mode. In addition to the S3 chip (the focus of this paper), the S1, S2, S4, I3, and 14 chips were also read out.

Fig. 1.—A 4.5 $\times$ 2.2 optical photograph of NGC 7714/7715 from Arp (1966). North is up, and east is to the left. NGC 7714 is the larger galaxy to the west. Note the partial ring (1), the two western tails (2, 3), the northeastern tail of NGC 7714 (4), the bridge (5), and the eastern tail of NGC 7715 (6).
Initial data reductions were done using the CIAO, version 3.1 software. We tested for time intervals with high X-ray background, only included events with ASCA grades 0, 2, 3, 4, and 6, and removed standard bad pixels and columns. The energy range was restricted to 0.3–8 keV and then further divided into three ranges: 0.3–1, 1–2.5, and 2.5–8 keV. The binned images were adaptively smoothed using the CIAO routine csmooth, using a minimal significance of signal-to-noise ratio ($S/N = 2.5$) and a maximal significance of $S/N = 5$. The smoothed maps were then divided by a similarly smoothed exposure map to convert into physical units and to remove instrumental artifacts. We experimented with exposure maps created using different parameters, including both monochromatic maps at various energies and weighted maps. In all cases, the basic morphology of the extended emission remained the same, although the absolute flux level varied. For our final 0.3–8 keV map, we used an exposure map weighted by the spectrum of the 27''6 radius region centered on the NGC 7714 nucleus. For the final 0.3–1, 1–2.5, and 2.5–8 keV maps, we used monochromatic 0.8, 1.5, and 3 keV exposure maps, respectively.

3. RESULTS

3.1. Morphology

In Figure 3, the final smoothed Chandra images in various energy ranges are shown, with contours of the broadband optical light from the Digitized Sky Survey (DSS) superposed. In Figure 4, the Hα image from Smith et al. (1997) is superposed on the Chandra 0.3–8 keV map. An expanded view of the Chandra data, in contours, is superposed on Hα in Figure 5. The Chandra contours are overlaid on an archival Hubble Space Telescope (HST) WFPC2 broadband red F606W image in Figure 6. We registered the HST image by assuming that the brightest Chandra source is associated with the brightest source in the HST image; this also provides good alignment for the extranuclear H ii regions.

These figures show significant correlations between the diffuse X-ray emission and star formation. An extended arc of X-ray emission is detected along the inner western tail of NGC 7714, coincident with Hα emission (H ii region complex C; Fig. 5). Diffuse X-ray emission is also observed in the H ii region complexes northwest and north of the NGC 7714 nucleus (regions B and E in Fig. 5). Interestingly, the H ii region complex between these two complexes (region D) is not clearly detected in X-rays, even though it is brighter in Hα than complex E to its east. A fourth H ii region complex ≈6'' to the southeast of the nucleus (region A) is visible in Hα and X-rays, as well as in the HST map (Fig. 6), the radio continuum map of Condon et al. (1990), and the Brγ image of Kotilainen et al. (2001). For H ii regions A, B, C, and E, the radii inside of which 50% of the observed counts are contained are 1''5 (3 pixels = 270 pc), 2''7 (5.2 pixels = 500 pc), 5'' (10 pixels = 900 pc), and 1'' (2 pixels = 180 pc), respectively, compared to 0''5 (1 pixel) for the two brightest isolated point sources in the field, ULX candidates 4 and 12 (see § 3.3).

Figure 6 also shows diffuse X-ray emission extending 11'' (1.9 kpc) to the northeast of the nucleus. Faint extended Hα emission is seen in the inner portion of this feature. Comparison between the different images in Figure 3 shows that the diffuse X-ray–emitting gas generally has a soft X-ray spectrum compared to the point sources.

3.2. The Central Region of NGC 7714

The high-resolution Chandra map shows that there are two central X-ray sources separated by 1''5 (270 pc), with the brighter...
source being to the southwest (see Fig. 7a). The 0.3–8 keV X-ray luminosities for the nucleus and secondary source are $4.4 \times 10^{46}$ and $1.1 \times 10^{46}$ ergs s$^{-1}$, respectively (see § 3.4). Both sources are unresolved in the Chandra image, with the brighter source being centered between two image pixels. In the registered HST F606W image, there is a pointlike optical counterpart within $0.4$ of the fainter Chandra source (see Fig. 7b). This source is also visible in archival F300W, F380W, F555W, and F814W HST images (see § 4.3).

3.3. Point Sources

We used the CIAO wavdetect routine to search for point sources in the Chandra data. Our observations are sensitive to point sources at the distance of NGC 7714/7715 with 0.5–8 keV luminosities (assuming isotropy) greater than approximately $2 \times 10^{35}$ ergs s$^{-1}$, depending on spectral shape (flux density $\geq 10^{-15}$ ergs s$^{-1}$ cm$^{-2}$); wavdetect detected 13 sources near NGC 7714/7715 (see Fig. 8 and Table 1), in addition to the nucleus of NGC 7714.

Sources 3 and 13 are relatively far from the optical features of the galaxies and so are likely background. This leaves 11 candidate ULXs within the optical extent of the galaxy. Using source counts from the Chandra Deep Field (Brandt 2001; Rosati 2002) and extrapolating to our bandpass as in Humphrey et al. (2003), we expect $\approx 2$ background sources above our flux limit within the optical extent of the galaxy. Thus, most of these 11 point

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Fig. 3.—Smoothed Chandra maps of NGC 7714/7715 in various energy ranges, with optical DSS contours. Top: 0.3–8 keV, created using a weighted exposure map. Second from top: 0.3–1 keV, created using a monochromatic 0.8 keV exposure map. Third from top: 1–2.5 keV, created using a monochromatic 1.5 keV exposure map. Bottom: 2.5–8 keV, created using a monochromatic 3 keV exposure map.
sources are likely ULXs associated with NGC 7714/7715. Two of these sources, 4 and 12, are very bright, with 2657 and 1076 counts, respectively. Source 4, the object previously studied by Papaderos & Fricke (1998) and Soria & Motch (2004), lies in the NGC 7714 ring, as does source 5. Sources 8 and 9 are in the inner western tail, while source 1 appears associated with the eastern NGC 7715 tail. Sources 10, 11, and 12 may be associated with the outer western tail. Source 2 appears to be in the disk of NGC 7715. Sources 6 and 7 lie near the NGC 7714 bar.

Sources 1, 2, 3, 4, 11, 12, and 13, and possibly 9, are marginally visible in the XMM-Newton image of Soria & Motch (2004), while sources 5, 6, 7, and 8 are unresolved from the nucleus. Interestingly, source 12, which is extremely bright in the Chandra data, is faint in the XMM-Newton map, implying an increase of a factor of \( \approx 10 \) in luminosity since the XMM-Newton observations. It was not detected in the less sensitive 1994 ROSAT HRI observations of Papaderos & Fricke (1998).

Only two of the candidate ULX sources in Table 1 are associated with ongoing star formation: source 8, which is associated with H\( \alpha \) region C, and source 9, which is coincident with faint H\( \alpha \) emission on the Smith et al. (1997) H\( \alpha \) map. Source 6 is close to but offset from star formation regions in the inner disk of NGC 7714 (see Figs. 5 and 6). None of the other ULX candidates have optical counterparts on archival HST or DSS images.

No X-ray counterpart was found in the Chandra data for SN 1999dn, a Type Ib (H-poor) supernova 14\( \arcsec \) southeast of the nucleus (Deng et al. 2000), or for the possible supernova 2\( \arcsec \)W, 5\( \arcsec \)N of the nucleus claimed by Mattila et al. (2002). Our upper limit to the 0.3–8 keV X-ray luminosity of these sources is \( \approx 2 \times 10^{38} \) ergs s\(^{-1}\).

X-ray detections of optically visible supernovae are uncommon. The Immler & Lewin (2003) compilation of X-ray supernovae contains only 15 detections, with X-ray luminosities of \( 10^{37} – 10^{40} \) ergs s\(^{-1}\). Of these 15, none were Type Ib, and only three were Type Ic. More recently, four additional Type Ic supernovae
Fig. 6.— Superposition of the Chandra 0.3–8 keV map (contours) on an archival HST F606W WFPC2 image of NGC 7714, after registering the HST map so that the brightest X-ray source is coincident with the brightest optical source. Note the X-ray counterparts to the H II regions to the northwest, northwest, and southeast of the nucleus. There are no obvious optical counterparts to the four candidate ULX sources in the field.

Fig. 7.— Left: Close-up view of the inner 10″ of the Chandra 0.3–8 keV map (both contours and gray scale). Note the second point source ≃1′.5 northwest of the nucleus. The extended source to the southeast is H II region complex A. Right: Chandra contours for the inner 10″, superposed on the archival HST F606W image. Note the bright optical point source within 1 Chandra pixel of the secondary X-ray source.
were detected, bringing the count to seven (Pooley 2004). The Type Ib/c supernova 2001em in UGC 11794 was detected by Chandra with a very high luminosity of $\approx 10^{41}$ ergs s$^{-1}$ (Pooley & Lewin 2004), significantly higher than our upper limit for SN 1999dn.

3.4. X-Ray Spectra

X-ray spectra for various regions in the NGC 7714/7715 field were extracted using CIAO, and spectral fitting was done using the ISIS data reduction package (Houck & Denicola 2000). The best-fit parameters are given in Table 2, and the fits are plotted against the observed spectra in Figure 9. Before fitting the spectra, the data were rebinned into 20 counts bin$^{-1}$. The fits in Table 2 were made using the 0.5–8 keV range; similar results were found with 0.3–8 keV. The quoted uncertainties are 90% confidence level. To estimate background counts, the deep ACIS observations of blank fields provided by the ACIS calibration team were used (file acis7sD200-12-01bkgrndN0002.fits), after reprojection and scaling to our observations. These background counts are consistent with, but have higher S/N than, counts from selected regions at the edge of our field.

The spectrum of the NGC 7714 nuclear region (within a radius of $0\degr 86 = 150$ pc) could be fitted to a MEKAL function with $kT = 9^{+4}_{-2}$ keV and a column density $n_H$ of $1.5^{+0.3}_{-0.4} \times 10^{21}$ cm$^{-2}$. The abundance is not well constrained by this fit ($\approx 2$ solar). An absorbed power-law function also produces a good fit, with

![Fig. 7.—Continued](image)

![Fig. 8.—Smoothed 0.3–8 keV Chandra map, with X-ray point sources marked (see Table 1). The contours are from the optical DSS. These point sources were selected by the CIAO wavdetect routine. Note that sources 4 and 12 are very bright. Interestingly, source 12 was very faint in the 2002 XMM-Newton observations of Soria & Motch (2004), with a brightness comparable to the other point sources in the field. Its X-ray luminosity has increased by a factor of about 10 in the Chandra observations. Sources 8 and 9 are associated with the inner western tail (and H\,ii regions; see Fig. 4). Sources 10, 11, and 12 may be associated with the outer western tail. Source 1 appears associated with the western NGC 7715 tail, while source 2 appears to be in the disk of NGC 7715. Sources 3 and 13 are likely background sources. No X-ray counterpart to the Type Ib SN 1999dn was detected.](image)
photon index $\Gamma = 1.7^{+0.1}_{-0.1}$ and $n_H = 2.2 \pm 0.2 \times 10^{21} \text{ cm}^{-2}$. The spectrum of the secondary nuclear source (in a radius of $0.6^\prime$) could be fitted to a power law with $\Gamma = 1.9^{+0.3}_{-0.3}$. This source requires a column density similar to that of the nucleus, $2.0^{+0.9}_{-0.7} \times 10^{21} \text{ cm}^{-2}$. No Fe-K emission was detected, with an upper limit of $\leq 1.2 \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2}$.

We extracted a spectrum for the extended emission in the central region of NGC 7714 using a circular region with a $9.5^\prime$ radius centered $1^\prime.5$ east, $2^\circ$ north of the nucleus, excluding the regions used for the nuclear and secondary source spectra and H ii region A $6^\prime$ southeast of the nucleus. The spectrum of this extended emission is consistent with that of a power law or single-temperature gas. It is well fitted by a two-temperature MEKAL function, with temperatures of $0.59^{+0.05}_{-0.06}$ and $8.1^{+1.0}_{-0.4}$ keV and a column density of $5.3 \times 10^{20} \text{ cm}^{-2}$. The spectrum can also be well fitted by a 0.6 keV MEKAL function plus a power law with $\Gamma = 1.8 \pm 0.2$. The total $0.3-8 \text{ keV}$ luminosity of this extended emission is $3.5 \times 10^{40} \text{ erg s}^{-1}$, with the 0.6 and 6 keV components contributing $1.1 \times 10^{40} \text{ erg s}^{-1}$ (33%) and $2.3 \times 10^{40} \text{ ergs s}^{-1}$ (67%), respectively. For both the two thermal plasma fits and the thermal plasma plus power law fits, we allowed the silicon abundance to be a free parameter (constrained to be the same for both plasmas), to account for the 2 keV feature seen in Figure 9. Both of these fits are consistent with a Si abundance near solar (1.2+0.6 for the former and 0.9+0.7 for the latter) and are marginally inconsistent with the 0.25 solar abundance assumed for the other metals. An enhancement of $\alpha$-elements such as Si compared to other elements is expected in starbursts, since they are predominantly produced by Type II supernovae (e.g., Arnett 1995).

We separated the extended emission into two zones, with the inner being a $3^\prime$ radius region centered on the nucleus (excluding the nucleus itself) and the outer being the remainder (excluding the secondary source and H ii region complex A). The spectra for both the inner and outer zones requires two components and were well fitted with either two thermal plasmas or a thermal plasma and a power law. The temperatures and spectral indices of these components were similar to those found above. The total

### Table 1: Candidate ULXs in the NGC 7714/7715 Field

| Source | Chandra Name (J2000.0 Coordinates) | Net Counts (0.3–8 keV) | $L_X$ (0.3–8 keV) | Apparent Location |
|--------|-----------------------------------|------------------------|------------------|------------------|
| 1................. | CXOU 233623.5+020933 | 10 $\pm$ 3 | 3 | NGC 7715 tail |
| 2................. | CXOU 233622.1+020923 | 28 $\pm$ 5 | 7 | NGC 7715 disk |
| 3................. | CXOU 233619.3+020839 | 50 $\pm$ 7 | 12 | Background |
| 4................. | CXOU 233615.6+020923 | 2657 $\pm$ 52 | 640 | NGC 7714 ring |
| 5................. | CXOU 233615.1+020904 | 21 $\pm$ 5 | 5 | NGC 7714 ring |
| 6................. | CXOU 233614.2+020908 | 21 $\pm$ 5 | 6 | Near end of NGC 7714 bar |
| 7................. | CXOU 233613.9+020936 | 26 $\pm$ 5 | 7 | Near end of NGC 7714 bar |
| 8................. | CXOU 233613.2+020902 | 30 $\pm$ 6 | 8 | Inner western NGC 7714 tail |
| 9................. | CXOU 233612.3+020905 | 22 $\pm$ 5 | 6 | Inner western NGC 7714 tail |
| 10.............. | CXOU 233611.5+020853 | 10 $\pm$ 3 | 3 | Outer western NGC 7714 tail |
| 11.............. | CXOU 233610.1+020923 | 30 $\pm$ 6 | 8 | Outer western NGC 7714 tail |
| 12.............. | CXOU 233610.0+020900 | 1076 $\pm$ 33 | 240 | Outer western NGC 7714 tail |
| 13.............. | CXOU 233609.1+021007 | 20 $\pm$ 5 | 5 | Background |

### Table 2: Spectral Fits

| Source | Function | $\chi^2$/dof | $n_H \times 10^{21}$ cm$^{-2}$ | $\Gamma$ | $kT$ (keV) | [Si] | Net Counts (0.3–8 keV) | $L_X$ (0.3–8 keV) | $(10^{40}$ erg s$^{-1}$) |
|--------|----------|--------------|-------------------------------|---------|------------|------|------------------------|-----------------|-------------------|
| Nuclear$^a$ | MEKAL | 60/61 | 1.5$^{+0.3}_{-0.1}$ | ... | 9$^{+2}_{-4}$ | ... | 1498 $\pm$ 39 | 4.7 |
| Nuclear$^a$ | Power law | 60/61 | 2.2 $\pm$ 0.2 | 1.7$^{+0.1}_{-0.0}$ | ... | ... | 1498 $\pm$ 39 | 4.4 |
| Secondary source$^a$ | Power law | 17/23 | 2.0$^{+0.9}_{-0.7}$ | ... | 1.9$^{+0.3}_{-0.3}$ | ... | 480 $\pm$ 22 | 1.1 |
| Central diffuse$^b$ | MEKAL + MEKAL | 59/60 | 0.5$^{+0.2}_{-0.1}$ | ... | 0.59$^{+0.08}_{-0.07}$ | 1.2$^{+0.6}_{-0.8}$ | 1933 $\pm$ 44 | 3.5 |
| Central diffuse$^c$ | Power law | 59/60 | 1.0$^{+0.4}_{-0.3}$ | 1.8 $\pm$ 0.2 | 0.57$^{+0.18}_{-0.18}$ | 0.9 $\pm$ 0.7 | 1933 $\pm$ 44 | 3.5 |
| Inner diffuse$^d$ | MEKAL + power law | 27/40 | 0.7$^{+0.3}_{-0.2}$ | ... | 0.6$^{+0.12}_{-0.12}$ | 2.3$^{+0.2}_{-0.2}$ | 1163 $\pm$ 34 | 2.4 |
| Inner diffuse$^e$ | MEKAL + power law | 28/40 | 1.4$^{+0.5}_{-0.4}$ | 1.9$^{+0.4}_{-0.2}$ | 0.55$^{+0.10}_{-0.12}$ | 8.4$^{+0.5}_{-0.3}$ | 1163 $\pm$ 34 | 2.3 |
| Outer diffuse$^f$ | MEKAL + MEKAL | 19/23 | 0.5$^{+0.0}_{-0.1}$ | ... | 0.59$^{+0.02}_{-0.02}$ | 1.2$^{+0.2}_{-0.3}$ | 742 $\pm$ 28 | 1.2 |
| Outer diffuse$^g$ | Power law | 19/23 | 0.6$^{+0.4}_{-0.3}$ | 2.3$^{+0.6}_{-0.6}$ | 0.56$^{+0.07}_{-0.07}$ | 0.5$^{+0.4}_{-0.5}$ | 742 $\pm$ 28 | 1.1 |
| Point source 4$^h$ | Power law | 78/93 | 1.9 $\pm$ 0.3 | 1.9$^{+0.1}_{-0.0}$ | ... | ... | 2657 $\pm$ 52 | 6.4 |
| Point source 12$^h$ | Power law | 51/41 | 0.6 $\pm$ 0.5 | 1.6 $\pm$ 0.2 | ... | ... | 1046 $\pm$ 32 | 2.4 |

$^a$ Used pileup model with $\alpha = 0.5$ and psfract = 0.95 fixed. Models without pileup give consistent results.

$^b$ These parameters give acceptable fits for all abundances <2 solar.

$^c$ In a $9.5^\prime$ region centered $1^\prime.5E$, $2^\circ$N of the nucleus, excluding the two central point sources and H ii region A. The metal abundance was fixed at 0.25 solar. All abundances from 0.1 to 2 solar give acceptable fits with consistent parameters.

$^d$ The metal abundance, aside from [Si], was fixed at 0.25 solar. The abundance could not be constrained.

$^e$ In a $3^\prime$ region centered $1^\prime.5E$, $2^\circ$N of the nucleus, excluding the two central point sources. The abundances of the other elements besides silicon were fixed at 0.25 solar.

$^f$ In a $3^\prime$–$9.5^\prime$ annulus centered $1^\prime.5E$, $2^\circ$N of the nucleus, excluding the two central point sources and H ii region A. The abundance of the other elements besides silicon was fixed at 0.25 solar.
0.3–8 keV luminosity for the inner region is $2.4 \times 10^{40}$ ergs s$^{-1}$, with $17^{+13}_{-11}$% coming from the soft component and $83^{+1}_{-1}$% coming from the hard component. For the outer region, the total X-ray luminosity is $1.2 \times 10^{40}$ ergs s$^{-1}$, with $66^{+34}_{-16}$% from the cooler component and $34^{+16}_{-34}$% from the hard component. Thus, the fraction of hard radiation decreases with radius.

When separating the central diffuse spectrum into two regions, the evidence for a greater than solar silicon abundance for the inner region becomes stronger. Again, we have constrained the Si abundance to be the same in each component of the two plasma fits. The 90% lower limits for the Si abundance are 1.6 and 2.9 solar for the two thermal plasma and thermal plasma plus power law fits, respectively. As also discussed by Soria & Motch (2004), there is some evidence for abundance gradients when comparing the inner to outer region. In Figure 9, the silicon feature at 2 keV is greatly diminished for the outer diffuse region. However, the error bars on the Si abundance for the outer region are large and greatly overlap with those from the inner region. Thus, one can

![Background-subtracted Chandra spectra (data points), best-fit spectral fits (solid lines), and residuals (dotted lines) for various regions in the NGC 7714/7715 system. Top left: Nuclear spectrum, with power-law fit. Top right: Spectrum of secondary source near nucleus with power-law fit. Middle left: Spectrum for the inner diffuse gas of NGC 7714, excluding the two nuclear sources, fitted with two thermal plasmas. Middle right: Spectrum for the outer diffuse gas of NGC 7714, excluding H ii region A, fitted with two thermal plasmas. Bottom left: ULX candidate 4, with a power-law fit. Bottom right: ULX candidate 12, with a power-law fit. See text and Table 2 for more details.](image_url)
attribute the loss of the Si feature to being predominantly caused by the loss of the hard X-ray component, rather than specifically to an abundance gradient.

The extranuclear H ii region complexes had too few counts to fit X-ray spectra. Assuming a MEKAL function with a temperature of 6.0 keV, N_H = 2 × 10^{21} cm^{-2} (from the H i map of Smith et al. 1997) and abundances of 0.5 solar for H ii region A and 0.25 solar for the rest (from Gonzalez-Delgado et al. 1995), we obtain 0.3–8 keV luminosities for the H ii region complexes of 2 × 10^{38}–5 × 10^{39} ergs s^{-1} (see Table 3). Lowering the assumed temperature to 0.65 keV decreases these luminosities by a factor of 7, while lowering the column density by a factor of 10 decreases these values by 40%.

Only ULX candidates 4 and 12 were bright enough to be spectrally fitted. Source 4, the bright source in the ring, could be well fitted with an absorbed power law with Γ = 1.9^{+0.2}_{-0.1} and n_H = 1.9 ± 0.3 × 10^{23} cm^{-2}. For source 12, a single absorbed power law gave a reasonable fit (χ^2 = 1.24) for Γ = 1.6 ± 0.2 and a low column density of n_H = 6 ± 5 × 10^{23} cm^{-2}. Adding a thermal second component does not significantly improve this fit. For the fainter point sources in Table 1, we calculated their X-ray luminosities assuming Γ = 2.0 and n_H = 1.8 ± 10^{23} cm^{-2}, and assuming that they are at the distance of NGC 7714.

For the sources with too few counts to fit spectra, plotting X-ray colors on a color-color diagram can provide some indication of the photon index and column density. Following the lead of Prestwich et al. (2003), for the fainter candidate ULXs and the H ii regions in NGC 7714/7715, we plot the soft X-ray color (M − S)/(S + M + H) against the hard X-ray color (H − M)/(S + M + H) in Figure 10, where S is the counts in the 0.3–1 keV band, M is the counts in the 1–2 keV band, and H is the counts in the 2–8 keV band. We have overplotted curves indicating the colors of absorbed power laws with column densities from 10^{20} to 10^{24} cm^{-2}, and photon indices Γ = 1–4. Figure 10 shows that these objects have colors typical of luminous point sources in other galaxies (Prestwich et al. 2003; Schwarz et al. 2005). The inferred column densities and photon indices for ULX candidates 4 and 12 are reasonably consistent with those obtained from the spectral fits (Table 2). The H ii regions have somewhat softer X-ray colors than the point sources, and regions B, C, and E appear somewhat less absorbed than H ii region A, as expected from their locations in the galaxy.

### 3.5. Variability

We have assessed the variability of the two nuclear sources and the remaining candidate ULX sources, 1–13, with the “Bayesian blocks” algorithm of J. D. Scargle et al. (2005, in preparation).^3^ The algorithm takes an event light curve and finds the “optimal partitioning” into piecewise-constant “blocks” of uniform rate. Thus, a variable light curve is represented as a series of step functions. The partitioning of the light curve is governed by a prior probability for the count rate in a block (here we choose this probability as ∝ e^{−λ/λ_0)}, where λ is the count rate and λ_0 is the mean rate over the entire light curve) and a prior probability for the number of blocks N_b that is ∝ γ^{N_b}. Thus, 1 − γ is, very roughly, similar to a “significance level” for each block; however, it should not be interpreted as a strict quantitative assessment of significance. The advantage of this algorithm is that it makes no prior assumption concerning the timescales of variability—either long- or short-timescale blocks can be found—nor on the location or number of the block boundaries. In the results described below, we find evidence for both short- and long-timescale variability.

We first apply the variability search to the primary nucleus. At values of 1 − γ < 0.96, the light curve is divided into three blocks. The first block has a duration of approximately 40 ks and a count rate of (2.72 ± 0.09) × 10^{23} counts s^{-1}, while the last block has a count rate of (2.31 ± 0.10) × 10^{23} counts s^{-1} and a duration of approximately 20 ks. The intervening block is only 128 s wide and contains 13 photons, for a nominal count rate of 0.10 ± 0.03 counts s^{-1}. Viewed individually, this nearly

Figure 10.—X-ray colors of H ii regions A, B, C, and E and ULX candidates 1–13, with the soft band being defined as 0.3–1 keV, the medium as 1–2 keV, and the hard as 2–8 keV. The dotted lines show the locations of absorbed power laws with photon indices of 4, 3, and 2, and 1, respectively, from left to right. The column density ranges from 10^{20} cm^{-2} at the lower left end of these curves, to 10^{24} cm^{-2} at the far right.
4. DISCUSSION

4.1. The Nuclear Extinction

The best fits to the X-ray spectra of the NGC 7714 nucleus and the secondary source near the nucleus both require reasonably high column densities of $N_{\text{HI}} \approx 2.2 \times 10^{21}$ cm$^{-2}$. This is higher than the sum of the H I absorption column density of $5 \times 10^{20}$ cm$^{-2}$ (Smith et al. 1997) plus the Galactic extinction of $\approx 3 \times 10^{20}$ cm$^{-2}$ (Burnstein & Heiles 1982; Stark et al. 1992; Schlegel et al. 1998). Our X-ray–derived column densities, however, are consistent with extinctions obtained from optical and near-infrared hydrogen recombinations, $A_V \approx 1$–2 (Puxley & Brand 1994; Calzetti et al. 1996; Kotilainen et al. 2001), which imply $N_{\text{HI}} \approx (2$–$4) \times 10^{21}$ cm$^{-2}$ using the standard ratio of $N_{\text{HI}}/E(B-V) = 5.8 \times 10^{21}$ cm$^{-2}$ mag$^{-1}$ (Bohlin et al. 1978). This suggests additional extinction from dust associated with molecular gas in addition to that associated with H I. H emission-line maps show a central depression in NGC 7714 (Smith et al. 1997), while 2.6 mm CO interferometric maps show a central $\approx 5'' \times 10''$ source elongated southeast-northwest (Ishizuki 1993). The CO surface brightness for this source is $\approx 25 \text{ K m s}^{-1}$, which corresponds to $N_{\text{H}_2} = 6.5 \times 10^{21}$ cm$^{-2}$, using the standard Galactic $N_{\text{H}_2}/(1\text{K CO})$ ratio of Bloemen et al. (1986). This is consistent with column densities based on the X-ray and hydrogen recombination line data.

4.2. The Origin of the X-Rays from the Nuclear Starburst

Possible contributors to the X-ray emission from a nuclear starburst include supernovae, O stars, Wolf Rayet (W-R) stars, hot gas, high-mass X-ray binaries (HMXBs), ULXs, and an obscured AGN. In the NGC 7714 nucleus, supernovae and hot stars are likely to be minor factors. In their stellar synthesis study of the inner 0.05' (150 pc) radius of NGC 7714, González-Delgado et al. (1999) obtained a starburst age of 5 Myr, with a supernova rate of 0.007 yr$^{-1}$. With new optical and near-infrared data, Lâncion et al. (2001) updated this model and concluded that an older population was also required. One possibility is a second intermediate-age (20 Myr) burst, which boosts the predicted supernova rate by a factor of $\approx 10$. Assuming an average $L_X \approx 2 \times 10^{36}$ ergs s$^{-1}$ per supernova and a timescale of $\approx 2 \times 10^4$ yr for supernova remnants (Cowie et al. 1981; Williams et al. 1997), the X-ray luminosity from supernovae is $\approx 3 \times 10^{39}$ ergs s$^{-1}$, less than 10% of the absorption-corrected Chandra X-ray luminosity of the nucleus of $4 \times 10^{40}$ ergs s$^{-1}$. Typical X-ray luminosities for O stars and W-R stars are $\approx 10^{31}$–$10^{32}$ and $\leq 10^{33}$–$10^{35}$ ergs s$^{-1}$, respectively (Sciortino et al. 1990; Guerrero...
The NGC 7714 nucleus has ≈2000 W-R stars and ≈16,600 O stars (González-Delgado et al. 1999), implying a total \( L_X \approx 10^{36} - 10^{39} \) ergs s\(^{-1}\) from these stars, less than 1% of the observed X-ray luminosity.

The contribution from hot gas heated by injection of mechanical energy from supernovae is more uncertain. Assuming each supernova contributes \( 10^{51} \) ergs of kinetic energy, the Lancer et al. (2001) supernova rate implies a mechanical luminosity from the supernovae of \( L_X \approx 2 \times 10^{32} \) ergs s\(^{-1}\), 50 times larger than the Chandra X-ray luminosity for this region. This indicates that mechanical energy from supernovae is sufficient to account for the X-ray luminosity if the efficiency of converting this mechanical energy into X-rays \( L_X/L_{\text{mech}} \) is greater than \( \approx 2\% \). We discuss this X-ray production factor \( L_X/L_{\text{mech}} \) further in § 4.5; at the present time it is quite uncertain.

Another possible source of nuclear X-ray emission is HMXBs, which are associated with a young stellar population. For Local Group galaxies, Helfand & Moran (2001) found ratios of the total X-ray luminosity from HMXB, \( L_X(\text{HMXB}) \), to the number of O stars of \( (2-20) \times 10^{34} \) ergs s\(^{-1}\) star\(^{-1}\). These ratios imply that less than 10% of the nuclear X-ray flux from NGC 7714 is due to HMXBs. This limit is uncertain, however, since the Helfand & Moran (2001) ratios are averaged over entire galaxies with a range of stellar ages. In a single coeval star formation region, one would expect no HMXBs until stars start evolving off the main sequence, after which \( L_X(\text{HMXB})/L_{\text{H}0} \) will increase. The evolution of the HMXB luminosity function and \( L_X(\text{HMXB})/L_{\text{H}0} \) in starbursts is still not well determined; thus, how much HMXBs contribute to the X-ray emission from the nuclear region is still uncertain.

Alternatively, the unresolved nuclear emission may be caused by either a low-luminosity AGN or one or more ULX-like objects. This idea is supported by the possible variability of the nucleus, which suggests that the emission is dominated by a single source or a few sources. The X-ray spectrum and luminosities are consistent with those of both AGNs and ULXs (Schwarz et al. 2005); however, as noted earlier, Spitzer infrared spectra show no evidence for an obscured AGN (Brandl et al. 2004). The upper limit to the luminosity of the Fe-K line from the nucleus is \( 2 \times 10^{39} \) ergs s\(^{-1}\). Comparing with the far-infrared luminosity of \( 8.3 \times 10^{33} \) ergs s\(^{-1}\) (David et al. 1992) gives \( L_{\text{IR}}/L_{\text{FIR}} \leq 2.4 \times 10^{-5} \), 1–2 orders of magnitude lower than that of typical type 2 Seyfert galaxies (Ptak et al. 2003), which argues against an obscured AGN. Furthermore, the 128 s flare followed by a diminution of the X-ray flux is similar to the X-ray flares seen in the microquasar GRS 1915+105 immediately preceding radio ejection events (e.g., Belloni et al. 1997). If this flare is real, then assuming that its timescale must be longer than a dynamical timescale, e.g., the orbital period at the innermost stable circular orbit of a Schwarzschild black hole, limits the compact object mass to \( \lesssim 3 \times 10^5 M_\odot \). This mass limit also argues against an obscured AGN.

4.3. The Secondary Nuclear Source

The secondary nuclear source in NGC 7714 may be an ULX, having an X-ray luminosity and power-law spectrum consistent with that of the ULXs studied by Schwarz et al. (2005). We obtained HST WFPC2 magnitudes for the possible optical counterpart to this source using the IRAF software\(^4\) with a 4 pixel radius aperture and an annulus for sky subtraction with inner and outer radii of 7 and 11 pixels, respectively. After doing an aperture correction as in Holtzman et al. (1995b) and the WFPC2 Data Handbook, the F300W, F380W, F555W, F606W, and F814W magnitudes are 17.5, 18.0, 18.8, 18.7, and 19.2, respectively. Iteratively using the conversions in the IRAF SYNPHOT database, we find \( V \approx 18.8, U - B \approx -0.6, B - V \approx -0.1 \), and \( V - I \approx -0.4 \).

As discussed in § 4.1, the extinction to the ionized gas in the nuclear region is \( A_V \approx 1–2 \). However, from the slope of the UV spectrum, González-Delgado et al. (1999) conclude that the stars in the nuclear region that are contributing to the UV flux are significantly less obscured on average than the ionized gas, \( A_V \approx 0.1 \). A low extinction is consistent with the very blue optical colors of this source, typical of B stars. The absolute \( V \) magnitude of this optical source is therefore \( \approx -14.1 \) or brighter. This magnitude and the optical diameter of \( \lesssim 30 \) pc are consistent with those of the brightest of the so-called super star clusters often found in HST images of interacting galaxies, which are believed to be very young globular clusters (Whitmore et al. 1993, 1999; Whitmore & Schweizer 1995; Zepf et al. 1999; Holtzman et al. 1992, 1996; Elmegreen et al. 2001). This source is bluer than most of the super star clusters found to date (Whitmore et al. 1999; Zepf et al. 1999; Elmegreen et al. 2001), with colors that imply a cluster age of less than 4 Myr (Leitherer et al. 1999).

This optical source is just one of more than 20 such optical clusters seen in the inner region of NGC 7714 (see Fig. 7b); thus, it is possible that it is just a chance alignment of an optical cluster with the ULX. Assuming the association is correct, this source has an apparent X-ray–optical ratio of \( \log (F_X/F_V) \approx -0.3 \) (calculated as in Maccacaro et al. 1988). This source is somewhat bluer and more optically luminous than the possible optical counterparts to about a dozen ULXs found in the Antennae galaxy \( (M_V = -10 \text{ to } -13.7, B - V = 0 - 0.8, \log (F_X/F_V) = -1.5 \text{ to } 0.7) \); Zezas et al. 2002). Excluding the Antennae sources, most optical counterparts to ULXs found so far are much less optically luminous than the NGC 7714 source, but similarly blue. In Table 4, we tabulate information about other possible optical counterparts to ULXs from the literature. The NGC 1637, M81, M82, Einstein 11, M83, and NGC 5204 ULXs have similar optical colors, but much lower optical luminosities (Stocke et al. 1991; Immler et al. 1999, 2003; Liu et al. 2002, 2004), while the NGC 4565 source and the M82 MGG-11 source are both redder and less luminous (Wu et al. 2002). Most of these other ULXs have optical magnitudes and colors consistent with single O and B stars; thus, they may be compact objects in accreting binary systems. In contrast, the NGC 7714 and Antennae ULX optical counterparts are consistent with very luminous young star clusters. Perhaps these sources are accreting binary systems within or recently ejected from very young star clusters.

The optical magnitude of the apparent optical counterpart to the secondary nuclear source in NGC 7714 is similar to the nuclei of the “normal” non-AGN spirals studied by Phillips et al. (1996) and Böker et al. (2004), who suggest that these nuclei are simply compact star clusters. This source is about 5 mag less luminous in \( F \) than typical Seyfert nuclei (Chen et al. 1985; Granato et al. 1993); thus, it does not appear to be a second obscured nucleus. The presence of variability argues that the majority of the X-ray emission is likely associated with a single source; however, the timescales involved do not strongly limit the mass of the emitting object. The observed variability could be consistent with either a stellar mass or supermassive black hole.

\(^4\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
A optical cluster MGG-11 has been noted by Portegies Zwart et al. 2004. MGG-11 has an observed 4.5 Mpc (Thim et al. 2003); (7) Wu et al. 2002; (8) UV optical spectra and fluxes consistent with B0 Ib star (Liu et al. 2004).

(5) Seen in X-ray binaries (LMXBs), which are associated with the older assumed to be due to unresolved X-ray binaries, either low-mass superwind with X-rays. In some cases, in addition to one or two components at 0.6, 0.9, and 3.9 keV were fitted to the extended emission in the central region of NGC 7714 (Griffith et al. 2000; 7) Immler et al. 1999, using a distance of 4.5 Mpc (Thim et al. 2003); (7) Wu et al. 2002; (8) UV optical spectra and fluxes consistent with B0 Ib star (Liu et al. 2004).

4.4. The Superwind

4.4.1. The Age of the Superwind

The extended X-ray emission in the central region of NGC 7714 may be due at least in part to a superwind from the nucleus. The 1.9 kpc radial extent of this emission can be used to estimate the age of the superwind, assuming it is a “superbubble” of hot gas produced by the combined effect of supernova and stellar winds from the nuclear starburst. The expansion timescale of a superbubble can be estimated from $t_\text{exp} \approx 2.8 \times 10^7 \frac{L_{\text{mech}} n_1^{1/2}}{r_{\text{shell}}}$, where $t_\text{exp}$ is the timescale in units of $10^7$ yr, $L_{\text{mech}}$ is the mechanical energy of the supernovae in units of $10^{52}$ ergs s$^{-1}$, $n_1$ is the average hydrogen number density in units of $1$ cm$^{-3}$, $\eta \approx 0.1$ is the efficiency of the kinetic energy deposited into the gas (Dyson & Williams 1980), and $r_{\text{shell}}$ is the radius of the bubble in kpc (Shull 1995; Taniguchi et al. 2001). Using $L_{\text{mech}} \approx E_{\text{SN}} n_1^{1/3} E_{\text{SN}} \approx 10^{51}$ ergs $\approx$ the energy of a single supernova, and hydrogen number density $n_1$ $\approx 1$ cm$^{-3}$ gives $L_{\text{mech}} \approx 2.3 \times 10^{41}$ ergs s$^{-1}$, using a supernova rate $E_{\text{SN}}$ of 0.07 yr$^{-1}$. This implies a timescale of $\approx 15$ Myr for the bubble. Allowing time for supernova activity to begin, this timescale is consistent with the age inferred for the possible intermediate-age starburst in NGC 7714 (Lacon et al. 2001), which is likely the dominant source of the supernovae that power this wind ($\S$ 4.2).

4.4.2. The Hard Component of the Extended Emission

The extended emission seen in Chandra observations of many starburst galaxies can be fitted to temperatures ranging from 0.1 to 0.9 keV, without needing a hard component (e.g., NGC 4631: Wang et al. 2001; NGC 4676: Read 2003; NGC 4038/4039: Fabbiano et al. 2003, 2004; NGC 4449: Summers et al. 2003; NGC 1800: Rasmussen et al. 2004). In contrast, spectral fitting of the extended emission in NGC 7714 requires a second hard component in addition to a colder thermal component. NGC 7714 is not unique, however. In M82, a 2–5 keV diffuse component has been detected (Griffith et al. 2000; Strickland et al. 2004a), while in NGC 3256 three thermal components at 0.6, 0.9, and 3.9 keV were fitted to the extended emission (Lira et al. 2002). In some cases, in addition to one or two 0.1–0.9 keV thermal components, a hard power-law component was also included in the fit (NGC 4214: Hartwell et al. 2004; NGC 5253: Summers et al. 2004; M83: Soria & Wu 2002).

A hard, spatially extended component in galaxies is often assumed to be due to unresolved X-ray binaries, either low-mass X-ray binaries (LMXBs), which are associated with the older stellar population, or the HMXBs discussed in § 4.2. An upper limit to the X-ray luminosity from LMXBs can be obtained from the lower envelope of the global $L_X$ versus $L_\beta$ plot for elliptical and S0 galaxies (Canizares et al. 1987; Ciotti et al. 1991). In X-ray–faint, gas-poor, early-type galaxies without much ongoing star formation, the total X-ray luminosity is an upper limit to the emission from LMXBs. This limit is $L_X \approx 1.5 \times 10^{40} L_\beta / (10^{11} L_\odot)$ ergs s$^{-1}$ (Ciotti et al. 1991), where $L_X$ is defined as $L_X = \text{d}x / (0.4(M_4 - 5.41))$ (Canizares et al. 1987). Since Chandra observations of some of these X-ray–faint, early-type galaxies show that at most $\approx 30\%$ of this flux can be attributed to unresolved LMXB with $L_X \approx 10^{40}$ ergs s$^{-1}$ (Sorazin et al. 2000; Sivakoff et al. 2003; O’ Sullivan & Ponmon 2004), this limit can be lowered by a factor of $\approx 3$. These conversions are somewhat uncertain, as the $L_X (\text{LMXB}) / L_{\beta}$ ratio for galactic bulges may vary from galaxy to galaxy (Irwin et al. 2002).

The uncorrected blue luminosity of NGC 7714 within a 21” aperture is $6.6 \times 10^9 L_\odot$ (Huchra 1977), approximately the area of the superwind. This is an overestimate of the light due to old stars, since it contains the starburst nucleus as well as H II region A. Using $A_V \approx 1$ as an upper limit to the extinction to the older stars in the disk (see § 4.1 and 4.3) gives $L_X (\text{LMXB}) \leq 2 \times 10^{39}$ ergs s$^{-1}$, $\approx 10\%$ of the extended hard X-ray component. Thus, LMXBs likely do not account for all of this hard radiation.

An estimate of the contribution by HMXBs to the extended X-ray emission in the NGC 7714 disk can be made from the Hα emission in the “superwind” region and the Helfand & Moran (2001) $L_X (\text{HMXB}) / O$ star ratio for Local Group galaxies. The total extinction-corrected Hα luminosity of NGC 7714 minus the H II regions and the inner $\approx 1"$ is $^{\approx 2.8 \times 10^{41}}$ ergs s$^{-1}$ (González-Delgado et al. 1995, 1999). This implies $L_X (\text{HMXB}) \approx 1.0 \times 10^{40}$ ergs s$^{-1}$, $\approx 5\%$ of the hard X-ray luminosity of this region. Thus, HMXBs may be responsible for at least part of this hard radiation.

Another possible source of extended hard X-rays in a starburst galaxy is inverse Compton radiation caused by the interaction of infrared photons with supernova-generated relativistic electrons, as suggested for the starburst galaxies M82 and NGC 3256 (Rieke et al. 1980; Schaaf et al. 1989; Moran & Lehnert 1997; Moran et al. 1999). In this scenario, the hard X-ray photon index $\Gamma$ should be equal to $\alpha + 1$, where $\alpha$ is the radio spectral index ($F_\nu \propto \nu^{-\alpha}$). At high spatial resolution, the radio continuum emission in the core of NGC 7714 is extended over $\approx 6''$, with a 5 GHz flux density of $\approx 17$ mJy and a 5 GHz/1.4 GHz spectral

| Galaxy   | ULX | $M_\alpha$ | $M_\beta$ | $U - B$ | $B - V$ | $V - I$ | $B - I$ | $\log(F_X/F_\nu)$ | Reference |
|----------|-----|------------|-----------|---------|---------|---------|---------|------------------|-----------|
| NGC 7714 | I15  | 14.2       | 14.1      | -0.6    | -0.1    | -0.4    | -0.5    | -3               | 1         |
| NGC 1637 | 68   | ...        | -7.55     | ...     | ...     | -0.3    | ...     | 1.13             | 2         |
| M81       | X-11 | -4.3       | -4.2      | -0.1    | ...     | ...     | 3.0     | 3                | 3         |
| M82       | MGG-11 | 4       | ...       | ...     | ...     | ...     | ...     | 4                | 4         |
| M82       | Einstein 1 | -5.5 | ...       | ...     | <0.3    | ...     | ...     | 500              | 5         |
| M83       | H30  | ...        | -9        | 0       | ...     | ...     | 0.58    | 6                | 6         |
| NGC 4565 | RXJ 1236.2+2558 | -4.9 | ...       | ...     | ...     | 1.1     | 540     | 7                | 7         |
| NGC 5204 | U1   | ...        | ...       | ...     | ...     | ...     | ...     | ...              | 8         |
4.5. Extended X-Ray Emission from H II Region Complexes

4.5.1. Contributions from HMXBs

We have detected extended X-ray emission from four extranuclear H II region complexes in NGC 7714. In Table 3, we compare the 0.3–8 keV X-ray luminosities for these H II region complexes with the number of Lyman continuum photons $N_{lyc}$ and Hα luminosities, after correction for an average extinction of $A_V = 0.7$ (González-Delgado et al. 1995). As in the nuclear region, the two most likely contributors to the extended X-ray emission from these regions are HMXBs and hot gas produced by stellar winds and supernovae impacting the ambient interstellar medium. The Local Group $N_{lyc}/L_X$ (HMXB) ratios are $\approx (3-60) \times 10^{13}$ (Helfand & Moran 2001); thus, except for region D, the X-ray luminosities for these H II regions are larger than expected for HMXBs. This indicates either other contributions to the X-ray flux or an $L_X$ (HMXB)$/N_{lyc}$ ratio higher than the galactic averages tabulated in Helfand & Moran (2001).

4.5.2. Contributions from Wind-Heated Gas

To estimate the contributions to the extended X-ray emission of these H II regions from wind-heated gas, we use theoretical models of the mechanical luminosity from supernovae and stellar winds in star clusters from the Starburst99 spectral synthesis software, version 4.0 (Leitherer et al. 1999). This version includes improvements to supernova-related quantities by M. Cervino and updated W-R and O star model atmospheres by Smith et al. (2002). To determine the X-ray luminosity, we need to assume an X-ray production factor $L_X/L_{mech}$, the fraction of the mechanical energy of the starburst that is converted into X-rays. Estimates of $L_X/L_{mech}$ in the literature vary widely, from 5% (Strickland & Stevens 1999), to 0.2% (Strickland et al. 2004b), to 0.02% (Dorland & Montmerle 1987). We discuss observational limits on $L_X/L_{mech}$ further in § 4.5.3.

In Figure 12, we plot the expected extinction-corrected $N_{lyc}/L_X$ and $L_{Hα}/L_X$ ratios from Starburst99 for H II regions as a function of star cluster age, including only contributions to the X-ray flux from mechanical energy input from stellar winds and supernovae, excluding point sources. We plot the expected theoretical values for eight different models in Figure 12. We include models with continuous star formation as well as models with an instantaneous burst of star formation. We include models with a Salpeter initial mass function (IMF; power-law index $\alpha = 2.35$) as well as models with $\alpha = 3.3$. We have also varied the metallicity from solar metallicity to 0.25 solar and $L_X/L_{mech}$ from 5% to 0.02%. Since supernovae do not occur until a burst is $\approx 3.6$ Myr old, the model X-ray luminosity before 3.6 Myr is due solely to stellar winds. After 6 Myr, the mechanical energy from the supernovae strongly dominates the production of X-rays, and between 3.6 and 6 Myr, both winds and supernovae contribute.

The NGC 7714 H II regions have $N_{lyc}/L_X$ and $L_{Hα}/L_X$ ratios consistent with the Starburst99 models if the ages are between 3.8 and 7 Myr (instantaneous burst) or $\geq 5$ Myr (if the star formation has been continuous) and if the X-ray production efficiency $L_X/L_{mech} \approx 5\%$. These age estimates are consistent with those determined independently by García-Vargas et al. (1997) using optical emission line strengths, photoionization modeling, and evolutionary synthesis models. For H II regions A, B, and C, García-Vargas et al. (1997) found ages of $5.0 \pm 0.5$, $3.5 \pm 0.5$, and $4.5 \pm 0.5$ Myr, and metallicities of 0.4, 0.2, and 0.2 solar, respectively, assuming a Salpeter IMF. Using the García-Vargas et al. (1997) ages, we have included points for these H II regions in Figure 12. This consistency with the Starburst99 predictions suggests that mechanical energy from supernovae does contribute significantly to the X-ray flux from these H II regions, if the X-ray production efficiency is high. We discuss $L_X/L_{mech}$ further in § 4.5.3.

The low $L_X/L_{mech}$ ($\approx 0.02\%$) instantaneous burst models also give $L_X/L_{Hα}$ ratios consistent with those observed, but only if the age is $\approx 15$ Myr, much larger than the García-Vargas et al. (1997) estimates. This implies, however, that when the H II regions were younger, their $L_{Hα}$ would have been unreasonably large ($L_{Hα} \approx 10^{43}$ ergs s$^{-1}$ at 5 Myr). Thus, if the X-ray production efficiency is low, supernovae heating is likely not the dominant source of X-ray production in these H II regions.

For completeness, in Table 3 we also include the extinction-corrected $N_{lyc}/L_X$ and $L_{Hα}/L_X$ ratios for the nucleus. These values are a factor of 3–36 times lower than those of the H II regions. In Figure 12, we have plotted the location of the NGC 7714 nucleus, using the starburst age of 5 Myr (González-Delgado et al. 1999; Lancón et al. 2001). As noted in § 4.2 and discussed by Lancón et al. (2001), $N_{lyc}/L_X$ for the nucleus is approximately a factor of 10 too low compared to that expected for a 5 Myr starburst (assuming a 5% X-ray production efficiency). This supports the idea that either there is an intermediate-age population present that boosts the supernova rate, or that there are X-ray–bright point source(s) contributing to the X-ray flux.

Table 3 and Figures 5 and 6 show that H II region E has an $N_{lyc}/L_X$ ratio a factor of 10 lower than that of the other NGC 7714 extranuclear H II regions. It is unclear at present whether this difference is caused by a difference in age or in extinction, since no direct estimate of the age or extinction of region E is available at present.

4.5.3. Comparison to Other H II Regions and the X-Ray Production Factor $L_X/L_{mech}$

At the present time, $L_X/L_{mech}$ is not well determined theoretically. Standard models of H II regions and superbubbles predict too many X-rays in young H II regions with stellar wind-driven bubbles (Rauw et al. 2002; Dunne et al. 2003; Townsley et al. 2003, 2005) and too few in older supernovae-driven bubbles (e.g., Chu & MacLow 1990; Wang & Helfand 1991; Oey 1996). In this section, we provide observational constraints on $L_X/L_{mech}$ by compiling X-ray luminosities for some well-studied Galactic and extragalactic H II regions and superbubbles from the literature (Table 5) and comparing to Starburst99 models and other estimates of $L_{mech}$. In Table 5, we also include published estimates of the number of Lyman continuum photons, $N_{lyc}$, and extinction-corrected $Hα$ luminosities, based on radio, infrared,
and/or optical observations. When available, Table 5 also contains information about the age of the associated star cluster from color-magnitude diagrams (note that in several cases more than one cluster with different ages is present in a single H\(\text{\textsc{ii}}\) region complex). In Figure 12, we have plotted the H\(\text{\textsc{ii}}\) regions in Table 5 that have estimated cluster ages with the Starburst99 models.

Although there are large uncertainties on the values in this table because of the extinction corrections, the different X-ray energy ranges used, and assumptions made about the X-ray spectrum, a general trend is apparent in Table 5 and Figure 12. The very young H\(\text{\textsc{ii}}\) regions (<3.6 Myr; with no supernovae activity) have very high \(N_{\text{LyC}}/L_X\) and \(L_{\text{H}\alpha}/L_X\) ratios compared to the older star formation regions. For these young H\(\text{\textsc{ii}}\) regions, the \(N_{\text{LyC}}/L_X\) and \(L_{\text{H}\alpha}/L_X\) ratios are not consistent with the Starburst99 predictions unless the X-ray production efficiency \(L_X/L_{\text{mech}}\) is very low. Comparing the \(L_X\) values for the less than 3.5 Myr old H\(\text{\textsc{ii}}\) regions in Table 5 with solar metallicity Salpeter IMF Starburst99 models gives X-ray production efficiencies \(L_X/L_{\text{mech}}\) that range from \(7 \times 10^{-5}\) to \(4 \times 10^{-3}\), with a median of \(2 \times 10^{-4}\) (0.02%). For some of the young H\(\text{\textsc{ii}}\) regions in Table 5, it is also possible to calculate \(L_{\text{mech}}\) more directly, by summing over the mass-loss rates \(\dot{M}\) and the terminal wind velocities \(V\) of the individual stars in the cluster: \(L_{\text{mech}} = \Sigma \dot{M}V^2\). Using mass-loss rates and terminal velocities from Stevens & Hartwell (2003) for the H\(\text{\textsc{ii}}\) regions in our sample, we obtained a similar median \(L_X/L_{\text{mech}}\) of \(10^{-4}\) (0.01%).

The very weak diffuse X-ray emission in young H\(\text{\textsc{ii}}\) regions has been noted before (Rauw et al. 2002; Dunne et al. 2003; Townsley et al. 2003, 2005) and is not well understood. Some suggested explanations for the low efficiency of forming X-rays in wind-driven bubbles include the escape of hot gas through blowouts and fissures in the interstellar medium, suppression of heat conduction by strong magnetic fields, the entrainment of cold material in the wind, and the dissipation of energy by turbulence.

On average, the older star formation regions in Table 5 have higher X-ray production efficiencies than the younger ones.
### Table 5

| Galaxy | H II Region/Superbubble | Distance (kpc) | Age (Myr) | Reference | $L_X$ (ergs s$^{-1}$) | $N_{\text{LyC}}$ (photons s$^{-1}$) | $L_{\text{LyA}}$ (ergs s$^{-1}$) | Reference | $L_{\text{LyA}}/L_X$ | $N_{\text{LyC}}/L_X$ (photons ergs$^{-1}$) |
|--------|-------------------------|---------------|-----------|-----------|----------------------|-------------------------------|--------------------------|-----------|-------------------|----------------------------------|
| Milky Way ...... | Orion | 0.5 kpc | ≤1 | 1 | ≤3.8 x 10$^{33}$ | 2 | 8.0 x 10$^{48}$ | 1 x 10$^{57}$ | 3 | ≥2600 | ≥1.9 x 10$^{15}$ |
| M8 = Lagoon | 1.4 kpc | 4 | 6.6 x 10$^{32}$ | 5 | 2.1 x 10$^{49}$ | 3 x 10$^{57}$ | 3 | 45000 | 3.3 x 10$^{16}$ |
| NGC 2244 = Rosette | 1.4 kpc | 2 | 6 | 2 x 10$^{32}$ | 7 | 5.8 x 10$^{49}$ | 8 x 10$^{57}$ | 3 | 400000 | 2.9 x 10$^{17}$ |
| NGC 3603 | 8.5 kpc | 1 | 8 | 2 x 10$^{34}$ | 9 | 1.1 x 10$^{51}$ | 1.5 x 10$^{59}$ | 3 | 100000 | 7.2 x 10$^{16}$ |
| M17 = Omega | 1.6 kpc | 1 | 10 | 2.5 x 10$^{33}$ | 11 | 1.8 x 10$^{50}$ | 2.5 x 10$^{58}$ | 12 | 200000 | 7.6 x 10$^{14}$ |
| Carina | 1.4 kpc | 1–6.2 | 13 | 4.6 x 10$^{34}$ | 14 | 4.4 x 10$^{50}$ | 6 x 10$^{58}$ | 3 | 13000 | 9.5 x 10$^{12}$ |
| W51 | 5.5 kpc | 0.4–2.3 | 15 | 4.5 x 10$^{33}$ | 16 | 1.7 x 10$^{51}$ | 2.4 x 10$^{59}$ | 17 | 53000 | 3.9 x 10$^{16}$ |
| RCW 49 | 2.3 kpc | 2–3 | 18 | 3 x 10$^{33}$ | 16 | 1.4 x 10$^{50}$ | 1.9 x 10$^{58}$ | 17 | 63000 | 4.6 x 10$^{16}$ |
| LMC............. | 30 Dor | 50 kpc | 2–5 | 19 | (2–6) x 10$^{37}$ | 20 | 1.1 x 10$^{52}$ | 1.5 x 10$^{60}$ | 3 | 300 | 2.2 x 10$^{14}$ |
| NI1 | 50 kpc | 4–5 | 21 | 8 x 10$^{53}$ | 22 | 7.3 x 10$^{50}$ | 1.0 x 10$^{79}$ | 23 | 1300 | 9.5 x 10$^{14}$ |
| DEM 152 | 50 kpc | >10 | 24 | 5.4 x 10$^{53}$ | 25 | 2.1 x 10$^{50}$ | 2.9 x 10$^{78}$ | 24 | 540 | 3.9 x 10$^{14}$ |
| DEM 25 | 50 kpc | 6 | 26 | 1.8 x 10$^{53}$ | 26 | 2.9 x 10$^{48}$ | 4.0 x 10$^{76}$ | 27 | 22 | 1.6 x 10$^{13}$ |
| DEM 301 | 50 kpc | 4.5 | 26 | 5.4 x 10$^{53}$ | 26 | 2.0 x 10$^{50}$ | 2.7 x 10$^{78}$ | 27 | 500 | 3.7 x 10$^{14}$ |
| DEM 50 | 50 kpc | 4.5 | 26 | 4.2 x 10$^{53}$ | 26 | 2.2 x 10$^{49}$ | 3.0 x 10$^{77}$ | 26 | 72 | 5.2 x 10$^{13}$ |
| SMC............. | NGC 346 | 59 kpc | 3 | 28 | 1.5 x 10$^{34}$ | 29 | 5.9 x 10$^{50}$ | 8.1 x 10$^{78}$ | ... | 54000 | 3.9 x 10$^{18}$ |
| NGC 4303...... | B/27 | 16.1 Mpc | ... | ... | 1.3 x 10$^{50}$ | 31 | 1.7 x 10$^{52}$ | 2.4 x 10$^{80}$ | 32 | 19 | 1.4 x 10$^{13}$ |
| F/69 | 16.1 Mpc | ... | ... | 1.1 x 10$^{50}$ | 31 | 2.3 x 10$^{52}$ | 3.2 x 10$^{80}$ | 32 | 28 | 2.0 x 10$^{13}$ |
| M101............. | NGC 5455 | 7.2 Mpc | ... | ... | 4.8 x 10$^{58}$ | 33 | 1.2 x 10$^{52}$ | 1.7 x 10$^{80}$ | 34 | 35 | 1.1 x 10$^{13}$ |
| NGC 5461 | 7.2 Mpc | ... | ... | 1.1 x 10$^{58}$ | 33, 35 | 3.7 x 10$^{52}$ | 5.1 x 10$^{80}$ | 34, 36 | 90 | 6.6 x 10$^{7}$ |
| NGC 5462 | 7.2 Mpc | ... | ... | 1.9 x 10$^{58}$ | 33, 35 | 1.8 x 10$^{52}$ | 2.5 x 10$^{80}$ | 36 | 130 | 9.6 x 10$^{13}$ |

* Extinction-corrected.

References.—(1) O’Dell 2003; (2) den Boggende et al. 1978: total X-ray luminosity from ANS, 1–8 keV. This is an upper limit to the diffuse emission; (3) Kennicutt 1984; (4) Sung et al. 2000; (5) Rauw et al. 2002: with XMM-Newton, 0.5–2 keV; (6) Park & Sung 2002; (7) Townsley et al. 2003: Chandra, 0.5–2 keV; (8) Sung & Bessell 2004; (9) Moffat et al. 2002: Chandra, energy range not given; (10) Hanson et al. 1997; (11) Dunne et al. 2003: from ROSAT, 0.5–2 keV; (12) Felli et al. 1984; (13) Tapia et al. 2003 and Carraro et al. 2004; (14) Seward et al. 1979: Einstein, 0.5–3 keV; (15) Okumura et al. 2000; (16) Townsley et al. 2005: Chandra, 0.5–8 keV; (17) Smith et al. 1978; (18) Piatti et al. 1998 and Carraro & Muan 2004; (19) Melnick 1985 and Brandt et al. 1996; (20) Norchi & Oegelman 1995: from ROSAT, 0.1–2.4 keV; (21) Parker et al. 1992; (22) MacLow et al. 1998: ROSAT, 0.5–2.4 keV; (23) Walborn & Parker 1992; (24) Oey & Massey 1995; (25) Dunne et al. 2001: ROSAT, 0.5–2.4 keV; (26) Oey 1996: Chandra, 0.1–2.4 keV; (27) Oey & Kennicutt 1997; (28) Bouret et al. 2003; (29) Stevens & Hartwell 2003; (30) Relaño et al. 2002; (31) Tschöke et al. 2000: from ROSAT, 0.1–2.4 keV; (32) Martin & Roy 1992; (33) Williams & Chu 1995; (34) Skillman & Israel 1988; (35) Kuntz et al. 2003, K. D. Kuntz 2004 (private communication); (36) Bosch et al. 2002.
Comparison with the Starburst99 instantaneous burst 0.25 solar metallicity Salpeter models for the greater than 3.5 Myr old LMC superbubbles in Table 5 gives a median \(L_X/L_{\text{mech}}\) of 2 \(\times 10^{-3}\) (0.2\%), with a large scatter (0.01\%–5\%). Thus, a larger fraction of the total wind energy gets converted into X-rays in bubbles powered by supernovae than in stellar wind-driven bubbles. With a continuous burst, the median \(L_X/L_{\text{mech}}\) is even higher, 7\%, with a range of 0.1\%–36\%. For three of the superbubbles in Table 5, Oey (1996) has calculated the mechanical luminosity directly by adding up contributions from the individual stars in the corresponding OB associations and accounting for stars that have already become supernovae. Comparing her \(L_{\text{mech}}\) values with the X-ray luminosities for the affiliated superbubbles, we find \(L_X/L_{\text{mech}} \approx 0.02\)–0.05 (2\%–5\%), higher on average than the Starburst99 results but overlapping in range. 

Given the scatter in the empirically determined X-ray production factors, it is possible that supernovae-driven winds are responsible for the observed X-rays in the NGC 7714 H \(\Pi\) regions. However, it is clear from Figure 12 that the NGC 7714 H \(\Pi\) regions have an X-ray excess compared to LMC superbubbles with similar ages. Thus, if hot gas is responsible for the extended X-ray emission in the NGC 7714 H \(\Pi\) regions, the X-ray production efficiency must be higher on average than in the tabulated LMC regions. Given the uncertainty in \(L_X/L_{\text{mech}}\), whether hot supernovae-heated gas or HMXBs are responsible for the extended X-ray emission from these H \(\Pi\) regions is still an open question. Further investigations are needed to better determine \(L_X/L_{\text{mech}}\) for wind-driven X-ray production.

4.5.4. Mimicking of ULXs in High-Redshift Galaxies

In galaxies more distant than NGC 7714, H \(\Pi\) region complexes similar to those in NGC 7714 may be unresolved with Chandra, mimicking ULXs. For example, in the Cartwheel galaxy, which is 3 times the distance of NGC 7714, more than a dozen unresolved (\(<0.3\)–1.5 kpc) X-ray sources are detected in the star-forming ring, with luminosities in the ULX range (Gao et al. 2003; Wolter & Trinchieri 2004). The sizes and X-ray luminosities of these sources are consistent with the H \(\Pi\) regions seen in NGC 7714, while He \(\II\) luminosities from J. Higdon (2004, private communication) give \(L_{\text{He}}/L_X\) ratios of \(\approx 0.3\)–24, similar to those of the H \(\Pi\) regions in NGC 7714. Thus, at least some of these Cartwheel sources may be similar to the NGC 7714 H \(\Pi\) regions and may be resolved at higher spatial resolution. Most of the ULXs found so far, however, are in closer galaxies and thus are clearly a different class, or classes, of objects.

4.6. The Candidate Ultraluminous X-Ray Sources

The luminosity functions of ULXs in galaxies appear to scale with star formation rate (Grimm et al. 2003; Humphrey et al. 2003; Schwarz et al. 2005), or perhaps with a combination of star formation rate and galaxy mass. Furthermore, ULX candidates tend to be positionally coincident with star formation regions; for example, most of the ULXs in the interacting galaxy M51 are associated with spiral arms (Terasma & Wilson 2004). This correlation with star formation has been used to argue for the beamed model of these sources (King et al. 2001) or, alternatively, for an intermediate-mass black hole scenario where accretion from molecular clouds is occurring (e.g., Krolik 2004).

In NGC 7714/7715, only two of the candidate ULX sources in Table 1 are associated with ongoing star formation, sources 8 and 9. Interestingly, of the 11 ULX candidates, eight appear to be in or near tidal features or the ring (1, 4, 5, 8, 9, 10, 11, and 12) and two are near the ends of the NGC 7714 bar (6 and 7), which may also have been produced by the interaction. One of the remaining sources, 2, lies near the center of NGC 7715, which is believed to be in a post-starburst state with a stellar population age of \(\approx 45\) Myr (Bemlühr 1993). This lack of association with star formation regions does not rule out the beamed stellar mass black hole scenario, however. In the high-mass X-ray binary population synthesis models of Rappaport et al. (2005), the ULX population is largest \(5\)–100 Myr after a burst of star formation. In their scenario, a larger ULX population is expected in post-starburst regions (or regions with ongoing star formation) than in very young bursts. In NGC 7714, it is possible that the tails and rings are post-starburst, since starbursts can be triggered in such features (e.g., Schombert et al. 1990). Near-infrared colors suggest that the ring may have older stellar population (Bushouse & Werner 1990), but at the present time no information about population ages in the NGC 7714 tails is available. The closest approach between the two galaxies occurred \(\approx 170\) Myr ago (Struck & Smith 2003); thus, it is possible that the formation of the ULXs in the tidal features, the ring, and the bar was triggered by the interaction.

The most luminous point source in the Chandra map, source 4, near the NGC 7714 ring was previously detected in two separate XMM-Newton observations in 2002 June and December (Soria & Motch 2004). The XMM-Newton luminosity increased by a factor of 2 between these two observations, with a 0.3–12 keV luminosity of 6.6 \(\times 10^{39}\) ergs s\(^{-1}\) in 2002 December. In the high-luminosity state, the XMM-Newton spectrum can be well fitted by a single power law, \(\Gamma = 2.6^{+0.7}_{-0.5}\), consistent with the uncertainties. Thus, the Chandra observations were also made during a high-luminosity state. The fact that this source is pointlike in the Chandra data and variable in XMM-Newton rules out the possibility that the X-rays are arising from hot gas heated by the impact of bridge material or nuclear outflow, as suggested by Papaderos & Fricke (1998) based on low spatial resolution data from ROSAT.

As noted earlier, source 12 has undergone a factor of 10 increase compared to previous XMM-Newton observations. This argues for a single pointlike source, although it does not distinguish between a low-mass or supermassive black hole. If the 19 s flare is real, however, this constrains the system mass to \(\lesssim 4 \times 10^9\) \(M_\odot\).

The Chandra column density for source 4, 1.9 \(\pm 0.3\) \(\times 10^{21}\) cm\(^{-2}\), is consistent with that found from XMM-Newton and with the HI column density from Smith et al. (1997). In contrast, for source 12, which is near the edge of the outer tail, the low column density is consistent with the Galactic foreground.

5. SUMMARY

We have obtained Chandra X-ray images of the prototypical nuclear starburst galaxy NGC 7714 and its companion NGC 7715. Our primary results are as follows:

1. The 0.3–8 keV luminosity of the inner 150 pc radius nuclear region of NGC 7714 is \(\approx 4 \times 10^{39}\) ergs s\(^{-1}\). This is high compared to the number of Lyman continuum photons, suggesting that it is due to an enhanced population of HMXBs, one or more ULXs, an obscured AGN, or hot gas efficiently heated by supernovae produced by an intermediate-age stellar population. The possible variability in the Chandra data suggests that a
single source contributes significantly to the observed X-ray flux; however, the timescale of variation and the lack of Fe K line emission argue against an AGN.

2. A second luminous ($L_X \approx 10^{40}$ ergs s$^{-1}$) point source is detected 15' (270 pc) northwest of the nucleus, with an apparent optical counterpart on HST images. The optical magnitude of this source ($M_V \approx -14.1$) and its blue optical colors ($B - V \approx -0.1$) are consistent with it being a very young (<4 Myr) globular cluster. This source is much more optically luminous than most optical counterparts to ULXs found to date; however, it has similar optical colors. This suggests that it may be a mass transfer X-ray binary with a young massive stellar companion, which resides in a young star cluster. The observed Chandra variability is consistent with this suggestion.

3. Diffuse emission extending 11'' (1.9 kpc) to the north of the nucleus is visible in the Chandra images. The X-ray spectrum can be fitted by two MEKAL functions, with temperatures of 0.59$^{+0.05}_{-0.06}$ and 8$^{+3.3}_{-0.3}$ keV, or with a 0.6 keV MEKAL function plus a $\Gamma = 1.9^{+0.9}_{-0.8}$ power law. The hard component contributes ~2/3 of the 0.3–8 keV luminosity. Much of this hard component may be due to HMXBs; however, inverse Compton radiation cannot be ruled out. The soft component is probably caused by a superwind powered by the nuclear starburst. The superbubble expansion timescale is ~15 Myr, consistent with the age of the intermediate-age stellar population suggested by Lançon et al. (2001). There is some evidence for an enhanced silicon abundance, especially in the innermost regions. The presence of an abundance gradient is less clear.

4. We have detected extended X-ray emission from four extranuclear H ii region complexes. The high X-ray luminosities relative to the extinction-corrected H$_\alpha$ luminosities imply that either an enhanced population of HMXBs or shock heating from supernovae with a high X-ray production efficiency ($\approx 5\%$) is responsible for the emission. The high X-ray fluxes of these star formation regions imply that they are at least 3.5 Myr old, so that supernovae and HMXBs have started to occur. These ages are consistent with previous estimates based on optical spectroscopy and photoionization modeling.

5. To better determine the X-ray production efficiency, we have compiled data on well-studied star formation regions in nearby galaxies. The median X-ray production efficiency is 0.02% for young (<3.5 Myr) H ii regions and 0.2%–7% for older star formation regions. Thus, it is possible that the extended emission in the NGC 7714 H ii region is due to hot gas; however, this is uncertain.

6. In addition to the luminous X-ray source near the nucleus, 11 other X-ray point sources are visible in the vicinity of NGC 7714/7715. Ten of these appear to be associated with features likely produced in the interaction, but only two are in star formation regions. One of these sources shows evidence of short-timescale (19 s) variability.

7. No X-ray emission was detected from SN 1999dn or the possible supernova noted by Mattila et al. (2002), with upper limits to the 0.3–8 keV luminosities of $\approx 2 \times 10^{39}$ ergs s$^{-1}$.

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