EXTRANUCLEAR X-RAY EMISSION IN THE EDGE-ON SEYFERT GALAXY NGC 2992

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Received 2005 February 15; accepted 2005 March 30

ABSTRACT

We observed the edge-on Seyfert 1.9 galaxy NGC 2992 with the ACIS CCD array on the Chandra X-Ray Observatory and found several extranuclear (r ≳ 3″) X-ray nebulae within 40″ (6.3 kpc for our assumed distance of 32.5 Mpc) of the nucleus. The net X-ray luminosity from the extranuclear sources is ~2.3 × 10^39 erg s^-1 in the 0.3–8.0 keV band. The X-ray core itself (r ≲ 1″) is positioned at R.A. 9°45′41″.95, decl. -14°19′34″.8 (J2000.0) and has a remarkably simple power-law spectrum with photon index Γ = 1.86 and intrinsic N_H = 7 × 10^{21} cm^{-2}. The near-nuclear (3″ ≤ r ≤ 18″) Chandra spectrum is best modeled by three components: (1) a direct active galactic nucleus (AGN) component from the wings of the point-spread function or an electron-scattered AGN component, with Γ fixed at 1.86, (2) cold Compton reflection of the AGN component with intrinsic absorption N_H = 10^{22} cm^{-2}, with approximately the same 0.3–8.0 keV flux as the direct component, and (3) a 0.5 keV low-abundance (Z < 0.03 Z_solar) thermal plasma, with ~10% of the flux of either of the first two components. The X-ray luminosity of the third component (the “soft excess”) is ~1.4 × 10^{40} ergs s^{-1}, or ~5 times that of all of the detected extranuclear X-ray sources. We suggest that most (~75%–80%) of the soft excess emission originates from a region between radii of 1″ and 3″, which is not imaged in our observation due to severe CCD pileup. We also require the cold reflector to be positioned at least 1″ (158 pc) from the nucleus, since there is no reflection component in the X-ray core spectrum. Much of the extranuclear X-ray emission is coincident with radio structures (nuclear radio bubbles and large-scale radio features), and its soft X-ray luminosity is generally consistent with luminosities expected from a starburst-driven wind (with the starburst scaled from L_FIR). However, the AGN in NGC 2992 seems equally likely to power the galactic wind in that object. Furthermore, AGN photoionization and photoexcitation processes could dominate the soft excess, especially the ~75%–80% that is not imaged by our observations.

Subject headings: galaxies: individual (NGC 2992) — galaxies: Seyfert — galaxies: spiral — X-rays: galaxies

1. INTRODUCTION

Although active galactic nuclei (AGNs) usually dominate the X-ray luminosity in Seyfert galaxies, luminous extranuclear X-ray emission regions (hereafter EXRs) extending out to radii of ~10^2–10^3 pc are fairly common. For example, of the six Seyfert galaxies studied with the Röntgensatellit (ROSAT) High Resolution Imager (HRI; spatial resolution ~10″, energy range 0.2–2.4 keV) by Wilson (1994), four show spatially extended (≥5″) soft X-ray emission. In all four cases, the extended X-ray emission is oriented along the same position angle as the nuclear radio structures or the extended narrow-line regions (ENLRs), suggesting a possible connection between the EXRs and the active nucleus. Typical soft X-ray luminosities of the extended emission are ~10^39–10^41 ergs s^{-1}.

Soft X-ray spectral features with similar luminosities were also commonly observed in large-aperture X-ray spectra of Seyfert galaxies, and it is possible that they are in fact the EXRs. In the standard AGN paradigm (e.g., see review by Antonucci 1993), type 1 Seyfert nuclei, which emit a power-law X-ray spectrum, are observed directly (i.e., with little or no absorption), since the line of sight to the nucleus is roughly perpendicular to the plane of the obscuring torus. Type 2 Seyfert nuclei are observed at larger angles from the torus symmetry axis, so the AGN is hidden behind the large absorbing column (N_H ≥ 10^{22} cm^{-2}) of the obscuring torus. Thus, a power-law model with varying degrees of absorption serves as a generic “baseline” model for AGN X-ray spectra (e.g., Mushotzky et al. 1980; Mushotzky 1982). However, as shown by Turner & Pounds (1989) and Turner et al. (1991), ≥50% of the type 2 Seyfert galaxies observed with the European X-Ray Observatory Satellite (EXOSAT) and Einstein show evidence for surplus X-ray emission in the soft band (E ≤ 2 keV) when the hard-band data are modeled reasonably well with a simple absorbed power law. This surplus emission is known as “soft excess.”

Since spatially resolved X-ray spectroscopy on arcsecond scales was not possible before the launch of the Chandra X-Ray Observatory, the origin of the soft excess was not well understood, but some possibilities included (1) X-ray emission from the AGN that “leaks” through holes in the obscuring torus, or possibly around it—the so-called partial covering scenario, (2) X-ray
emission from the AGN, scattered into our line of sight by electrons along the torus axis, or (3) emission from extranuclear X-ray sources, i.e., EXRs. Since EXRs can be detected with the \textit{ROSAT} HRI and \textit{Chandra}, it would be useful to know if they are as common as “soft excess,” and, in particular, if there is a direct relationship between the two. In specific cases, this seems to be true. For example, Weaver et al. (1995) conclude that extranuclear X-ray emission observed in a \textit{ROSAT} HRI image of the Seyfert galaxy NGC 2110 also produces the soft excess that is observed in the total galaxy Broad Band X-Ray Telescope (BBXRT) X-ray spectrum.

EXRs in some of the nearest Seyfert galaxies have already been studied with \textit{Chandra} (e.g., NGC 4151, Ogle et al. 2000; Yang et al. 2001; NGC 1068, Young et al. 2001; Cyg A, Young et al. 2002; NGC 3516, George et al. 2002; NGC 4388, Iwasawa et al. 2003). The extranuclear X-ray emission generally has a soft ($E \lesssim 2$ keV) spectrum and is typically spatially coincident with high-ionization optical ENLRs, such as [O iii] $\lambda 5007$ nebulae. Their X-ray spectra imply very low abundances ($Z \leq 0.1 Z_{\odot}$) when fitted with a simple one-component thermal plasma model. \textit{Chandra} grating spectra of the brightest regions are well modeled by photoionization and photoexcitation by the AGN (e.g., see Ogle et al. 2003), suggesting that there may not be a need at all for collisional excitation (thermal emission) due to a nuclear outflow. Young et al. (2001) conclude that the EXRs in the composite Seyfert-starburst galaxy NGC 1068 are not dominated by starburst phenomena. However, some hot X-ray gas must be produced by the central starburst and also by any AGN-driven outflows (jets or winds), if they are present. The key is to determine the balance between the outflow and the photoionization and photoexcitation components, since both should be present to some degree.

A more systematic statistical study of EXRs in Seyfert galaxies is needed to understand their nature: whether they are wind shocks, jet shocks (e.g., NGC 4528; Cecil et al. 1995), an expanding hot bubble of gas, or even discrete sources of X-ray emission located outside the nuclear region (e.g., NGC 1068; Wilson et al. 1992). Associating EXRs with the AGN is tempting, since the AGN can easily both provide enough energy to drive powerful shocks and provide enough high-energy photons to ionize gas out to kiloparsec scales. However, many type 2 Seyfert galaxies also have nuclear starbursts that can produce very luminous X-ray point sources (e.g., Fabbiano et al. 2001; Colbert et al. 2004) and drive galactic superwinds that emit diffuse soft X-ray emission (e.g., Heckman 2004; Strickland et al. 2004a, 2004b). By studying the EXRs with the excellent spatial and spectral resolution of \textit{Chandra}, we can make great progress in understanding the nature of EXRs, and by studying many of them, we can determine if there is an exact relationship with the very common soft excess observed in Seyfert galaxies. Here we report details from a single deep \textit{Chandra} Advanced CCD Imaging Spectrometer (ACIS) observation of an interesting case study.

We observed the edge-on Seyfert galaxy NGC 2992 with \textit{Chandra}, since it is known to have a galactic-scale outflow that has been well studied at many wavelengths: optical (e.g., Colbert et al. 1996b; Allen et al. 1999; Veilleux et al. 2001; Garcia-Lorenzo et al. 2001), near-infrared (e.g., Chapman et al. 2000), radio (Ward et al. 1980; Hummel et al. 1983; Colbert et al. 1996a), and X-ray (Colbert et al. 1998). This galaxy has a wide-angled galactic outflow (Veilleux et al. 2001) and a “diffuse” (as opposed to “linear”) subkiloparsec radio structure. Since there is heavy obscuration in the nuclear region, it is difficult to tell whether NGC 2992 has a strong nuclear starburst or not.

The galactic outflow in NGC 2992 may be quite different from those in Seyfert galaxies that have already been observed with \textit{Chandra} (e.g., NGC 2110, M51, and NGC 4151), which have linear nuclear radio structures. Understanding its origin in the EXRs and the outflows may offer important clues to the starburst-AGN connection. Since NGC 2992 has very well studied ENLRs and also has a kiloparsec-scale outflow, it is an ideal galaxy to study with \textit{Chandra}.

In Figure 1, we show a $V$-band image of NGC 2992 and its companion galaxy NGC 2993. This interacting pair is also known as Arp 245. A comprehensive multiwavelength study of the interacting system is presented in Duc et al. (2000). NGC 2992 has morphological type Sab, while NGC 2993 has type Sa (Sandage & Bedke 1994). The projected separation between the two galaxies is $\sim 3''$ (28 kpc, assuming a distance$^2$ of 32.5 Mpc). Optically luminous tidal plumes extending from both galaxies are evident in deep optical images (e.g., Sandage & Bedke 1994; Duc et al. 2000), and some evidence of them can be seen in Figure 1.

We describe the observations and data reduction in § 2 and give results in § 3. An interpretation of the X-ray emission as starburst-driven and AGN-driven winds is given in § 4.

\section*{2. OBSERVATIONS AND DATA REDUCTION}

The edge-on Seyfert galaxy NGC 2992 and its companion NGC 2993 were observed with the \textit{Chandra} X-Ray Observatory in the A04 cycle, on UT dates 2003 February 16–17 (Obs. ID 3956). The ACIS-S CCD array was used, and the pointing center was chosen such that the two galaxies were centered in the

\footnote{Assuming a Hubble constant $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$ \cite{Spergel2003} and a recessional velocity of 2311 km s$^{-1}$ \cite{Keel1996}, NGC 2992 is located at a distance of 32.5 Mpc, so 1" corresponds to 158 pc.}
back-illuminated S3 chip (CCD 7). As a result, the off-axis angle of the nucleus of NGC 2992 was $3^\circ/26$. The satellite roll angle was constrained to $353^\circ$ so that the CCD readout column would be oriented along the major axis of NGC 2992 and the anticipated readout “streak” (due to the very bright nuclear point source) would not interfere with X-ray emission extending along the galaxy’s minor axis. The total on-source EXPOSURE time of the level 1 events file was 50.23 ks, using a CCD frame time of 3.2 s. The CCD temperature during the observation was $-120^\circ$C.

The level 1 events data were reprocessed with the ACIS_REPROCESS_EVENTS script using the Chandra data reduction software package CIAO version 3.0.2 and Chandra calibration database CALDB version 2.26. No CTI correction was performed, which creates weighted ancillary response files (ARFs) and response matrix files (RMFs) for extended spatial regions. For CCD 7, this S/N corresponds to the number of counts and the areas, respectively, for the source and background.

3. RESULTS
3.1. Spatial Analysis

In Figure 2, we show several images of the large-scale X-ray emission from NGC 2992/2993. In 1992 and 1994, soft (0.2–2.4 keV) X-ray emission was detected from both galaxies with the ROSAT HRI instrument (Fig. 2a). For comparison with the HRI image, we constructed a soft X-ray image from the ACIS data, using photons with energies 0.3–2.4 keV (Fig. 2b). The readout streak, due to CCD pileup from the very bright X-ray nucleus of NGC 2992, is clearly seen in the ACIS images.

3.1.1. X-ray Point Sources

In addition to the very bright nucleus of NGC 2992, we detect 20 X-ray point sources in the ACIS CCD that includes the NGC 2992/2993 complex. We list X-ray properties of the 20 point sources in Table 1 and display the positions of the sources nearest to NGC 2992/2993 in Figure 3. There are four sources within the $R_{25}$ ellipses of the two galaxies: source 7 ($L_X \approx 10^{42}$ erg s$^{-1}$) is $17''$ (2.7 kpc) southeast of the nucleus of NGC 2992, and sources 9, 10, and 11 ($L_X \approx 5 \times 10^{39}$ ergs s$^{-1}$) are all within $10''$ (1.6 kpc) of the center of NGC 2993. There are three other sources within ellipses corresponding to $R = 2R_{25}$: source 5 (NGC 2992) and sources 8 and 13 (NGC 2993).

3.1.2. Position of the X-ray Nucleus

The X-ray point source in the nucleus of NGC 2992 is obviously the dominant source of X-ray emission. Its X-ray luminosity of $\sim 10^{42}$–$10^{43}$ ergs s$^{-1}$ (e.g., Gilli et al. 2000) indicates that the emission is most likely coming from the Seyfert nucleus (Ward et al. 1980). We determined the position of the X-ray core using two independent methods. We first fitted elliptical isophotes to the full-band X-ray image of the nuclear source, using the ELLIPSE task in STSDAS version 3.2 (with IRAF ver. 2.12.2). Next we obtained very accurate constraints for one dimension of the X-ray position by finding the centroid of the CCD readout streak.

The X-ray nucleus of NGC 2992 is positioned off-axis by $\approx 3''$26, so the ACIS point-spread function (PSF) is symmetric and approximately elliptical. In Figures 4a and 4b, we show gray-scale maps of the raw X-ray counts for all (both “good” and “bad”) event grades and for just the “good” event grades (see § 2). Grade migration due to pileup is not noticeable in the lowest three contours (30, 60, and 90 counts pixel$^{-1}$, where the pixel size is $0''492$) but is very noticeable at the fourth contour level (120 counts pixel$^{-1}$). For comparison, the three ellipses in Figure 4d are for best-fit surface brightnesses of 52, 75, and 110 counts pixel$^{-1}$.

The centroiding uncertainty for each of the three ellipses, as reported by the ELLIPSE routine, is very small ($\approx 0.1$ pixel, or $\approx 0''05$). The three positions differ by $\leq 0''25$, and we assume this to be the net uncertainty of this method. In Figure 4d, we show three $r = 0''25$ circles, labeled A, B, and C, for the inner, middle, and outer ellipses, respectively. Crosses are marked at the centers of the three circles.

As mentioned, we also used the readout streak in the ACIS image to constrain the position of the X-ray core. For very bright X-ray point sources, a significant number of events are detected during the very brief CCD readout (40 µs of each 3.2 s frame; see the Chandra Proposer’s Observatory Guide [POG]). At the end of the readout time, these events are left scattered along the CCD column of the X-ray point source. By rotating our ACIS image by the roll angle (7°5) and finding the best-fit image column for the center of the readout streak, we were able to construct a line in the original (unrotated) image that accurately estimates one linear dimension of the position of the X-ray core (see Figs. 4c and 4d). We used the IRAF task IMEXAMINE to fit Gaussian profiles across the streak for positions $\approx 30''$–100'' above and below the X-ray point source. The standard deviation for the best-fit column values was 0.3 pixels. As can be seen in Figure 4c, both our ellipse fitting and our streak readout method give consistent results.

A position midway between the three ellipse centroids and the readout streak marks our best estimate for the position of the NGC 2992 X-ray peak (R.A. 9$^h$45$''$41$''$.95, decl. $-14^\circ$19'34''8'' [J2000.0]). This position was estimated by eye; however, the uncertainty is a fraction of a pixel. We mark this position with a diamond in Figure 4d. The estimated nominal uncertainty in absolute astrometry for Chandra is $\approx 0''5$ (e.g., Aldcroft 2002). Thus, we also show an error circle for the position of the X-ray core as a dashed circle of radius 0''5. In § 4, we compare our measured position of the X-ray core with positions of features in other wavebands.

3.1.3. Near-nuclear X-Ray Emission

Here we concentrate on extranuclear emission within $\approx 10''$ of the X-ray nucleus of NGC 2992 ($\approx 1.58$ kpc at a distance of 32.5 Mpc). In Figure 5, we show gray-scale plots of the near-nuclear X-ray emission in four different energy ranges: very soft (0.3–0.5 keV), soft (0.3–1.0 keV), hard (4.0–8.0 keV), and...
We also show a smoothed image of the Chandra Ray Tracer (ChaRT)5 MARX PSF in the full band and compare it with a smoothed image of our full-band ACIS observation. The slight elongation of the PSF along PA $\sim 45^\circ$ is due to the source being off-axis by $\sim 3.3$. This elongation is noticeable in all of the full-band images and in the hard-band image. There is no obvious extended (i.e., asymmetric with respect to the elongated PSF) hard X-ray emission (Fig. 5e), but there is extended (asymmetric) soft X-ray emission from $\sim 2''$ to $4''$ (0.3–0.6 kpc) toward the southeast (see Figs. 5c and 5f).

5 See http://cxc.harvard.edu/chart.
TABLE 1

| Source (1) | R.A. (2) | Decl. (3) | S/N | Count Rate (10^{-3} s^{-1}) (4) | F_X (10^{-15} ergs s^{-1} cm^{-2}) (5) | L_X (log ergs s^{-1}) (6) | Notes (8) |
|-----------|---------|----------|-----|---------------------------------|---------------------------------|-----------------|----------|
| 1..........| 09 45 30.07 | −14 18 42.1 | 2.4 | 0.8 ± 0.2 | 4.2 | ... |
| 2..........| 09 45 33.74 | −14 15 26.4 | 17.5 | 5.6 ± 0.4 | 30.2 | ... |
| 3..........| 09 45 34.33 | −14 16 36.1 | 4.8 | 1.5 ± 0.2 | 8.3 | ... |
| 4..........| 09 45 35.57 | −14 17 42.7 | 4.5 | 1.4 ± 0.2 | 7.8 | ... |
| 5..........| 09 45 37.25 | −14 21 20.7 | 3.9 | 1.2 ± 0.2 | 6.2 | ... |
| 6..........| 09 45 39.10 | −14 23 21.4 | 2.1 | 0.7 ± 0.1 | 3.7 | ... |
| 7..........| 09 45 42.72 | −14 19 48.0 | 5.7 | 1.8 ± 0.4 | 9.8 | 39.1 ULX in NGC 2992 |
| 8..........| 09 45 44.76 | −14 22 20.7 | 2.2 | 0.7 ± 0.1 | 3.8 | (38.7) |
| 9..........| 09 45 47.88 | −14 22 01.5 | 25.7 | 8.2 ± 0.5 | 44.4 | 39.7 (NGC 2993) |
| 10..........| 09 45 48.17 | −14 22 06.5 | 22.0 | 7.0 ± 0.7 | 38.0 | 39.7 (NGC 2993), (SN 2003ao) |
| 11..........| 09 45 48.43 | −14 22 05.2 | 30.1 | 9.6 ± 0.7 | 52.1 | 39.8 (NGC 2993), (SN 2003ao) |
| 12..........| 09 45 49.95 | −14 19 05.7 | 4.5 | 1.4 ± 0.2 | 7.8 | ... |
| 13..........| 09 45 50.46 | −14 21 38.3 | 20.5 | 6.6 ± 0.4 | 35.4 | (39.7) |
| 14..........| 09 45 51.25 | −14 19 45.5 | 6.6 | 2.1 ± 0.2 | 11.4 | ... |
| 15..........| 09 45 51.83 | −14 20 10.6 | 2.4 | 0.8 ± 0.1 | 4.1 | ... |
| 16..........| 09 45 53.29 | −14 17 05.4 | 9.1 | 2.9 ± 0.3 | 15.7 | ... |
| 17..........| 09 45 53.46 | −14 23 55.5 | 2.1 | 0.7 ± 0.1 | 3.7 | ... |
| 18..........| 09 45 53.77 | −14 23 57.1 | 2.2 | 0.7 ± 0.1 | 3.9 | ... |
| 19..........| 09 45 55.96 | −14 21 14.4 | 7.7 | 2.5 ± 0.2 | 13.4 | ... |
| 20..........| 09 45 56.64 | −14 24 18.2 | 4.6 | 1.5 ± 0.2 | 7.9 | ... |

Notes.—Col. (1): Source number. Cols. (2) and (3): Right ascension and declination of the X-ray source, taken from XASSIST output (see http://www.xassist.org). Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Col. (4): XASSIST signal-to-noise ratio. Col. (5): ACIS count rate and the error in the count rate in the 0.3–8.0 keV band. Col. (6): Observed X-ray flux in the 0.3–8.0 keV band, assuming a simple absorbed power law with Γ = 1.8 and the Galactic hydrogen absorption column (5.26 × 10^{19} cm^{-2}; Dickey & Lockman 1990). Units are 10^{-15} ergs s^{-1} cm^{-2}. Col. (7): Logarithm of observed X-ray luminosity, assuming a distance of 32.5 Mpc, for point sources within the R_{25} ellipses of NGC 2992 and NGC 2993. Values in parentheses are for sources 5, 8, and 13, which are positioned outside the R_{25} ellipses but within ellipses corresponding to R = 2R_{25}. Col. (8): Notes. The SIMBAD sources within 0.10 of the X-ray position are listed in parentheses (centers of NGC 2992 and NGC 2993, and SN 2003ao).

Due to the severity of the CCD pileup ≤2.5 (see § 3.1.2), estimating the flux of this extended soft X-ray source within ~2.5 is not straightforward. The total number of 0.3–1.0 keV counts between 2.5 and 5.0 is 242 ± 16, 360 ± 19, 126 ± 11, and 60 ± 8 for the four quadrants 1^o–90^o, 91^o–180^o, 181^o–270^o, and 271^o–360^o, respectively. Under the assumption that the first and fourth quadrants are background plus AGN contamination, source SE (i.e., the second and third quadrants) has ~100–200 net counts in the 0.3–1.0 band. This equates to an observed 0.3–8.0 keV luminosity of ~1–2 × 10^{39} ergs s^{-1} for a 0.5 keV bremsstrahlung model with Galactic absorption.

Using the Einstein HRI (E ≈ 0.1–3.5 keV), Elvis et al. (1990) claimed to detect extended emission within a radius of 10" with an X-ray luminosity of ≈4 × 10^{31} ergs s^{-1} (adjusted for our distance, and using a 0.25 keV bremsstrahlung model with Galactic absorption). The Einstein emission was detected in the quadrant centered at PA ~ 23°, but no emission was found in the other three quadrants. Since this conflicts with our Chandra results, we suggest that the Einstein detection was either due to a variable X-ray source or was spurious.

3.1.4. Kiloparsec-Scale X-Ray Emission

Next we investigate extended X-ray emission on scales ≥10'' (≥1.6 kpc at 32.5 Mpc). To investigate the presence of any extended emission in our Chandra image, we computed X-ray counts in radial bins as a function of angle. We used eight 45° angular wedges, with the first octant starting at PA ~ 15.5° (see Fig. 6). Octants 1 and 5 were centered on the CCD readout streak and were ignored in the rest of the analysis.

We modeled the PSF of the X-ray core in a number of different ways, none of which were ideal. We first tried to simulate the...
PSF with ChaRT, using the spectrum of the X-ray core (§3.2.1) as an input model. The ChaRT simulation was performed with the same off-axis angle and telescope roll angle as our ACIS observation. The output SAOsac ray-tracing files were converted to event files with the MARX6 Chandra simulator. We plot radial profiles for the ChaRT MARX PSF in Figure 6a. The background level (0.1 counts pixel\(^{-1}\)) was added to the ChaRT MARX PSF.

We first tried to use radial profiles from three octants that appeared free of excess emission (regions 2, 6, and 8 in Fig. 6b). We found no significant excess emission for hard X-ray emission with energies \(\gtrsim 2.5\) keV but did find excess emission in the softer bands. Octant 6 appeared to have some possible excess X-ray emission, so we downgraded our radial profile to include only octants 2 and 8, both of which did not show significant excess after subsequent PSF subtraction (see Fig. 6d). The most significant excess extends eastward along PA \(\sim 190^\circ\), out to \(\sim 40^\circ\), roughly perpendicular to the galaxy disk (see Fig. 6c). Using the combined radial profiles from regions 2 and 8 for a PSF, we calculate an excess of 90 ± 22 X-ray counts in this octant, from 20\(^\circ\) to 40\(^\circ\) (3.2–6.3 kpc). We found three other regions that had significant (\(>3\) \(\sigma\)) excess over our model PSF (see Fig. 6d): a pointlike source in region 4 (source 7

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6 See http://space.mit.edu/CXC/MARX.
Fig. 5.—Near-nuclear X-ray emission in NGC 2992. Gray-scale ACIS images of the nuclear region. Note the extended soft X-ray emission from \~2\arcsec to 5\arcsec southeast of the nucleus (source SE) in panels (c) and (f). All images are displayed with a logarithmic gray-scale stretch. The gray-scale limits for (a–c) and (e) are \~10 to 55 counts pixel\(^{-1}\) (1 pixel = 0\arcsec 492). The gray-scale limits for the ChaRT PSF (d) and the very soft image (f) are \~3000 to 10,000 and \~2 to 10 counts pixel\(^{-1}\), respectively. Three dashed circles, centered on our best position for the X-ray core (\(\alpha = 3.1\).2), are drawn with radii 0\arcsec 492 (1 pixel), 5\arcsec, and 10\arcsec. Panels (b), (c), (e), and (f) are raw ACIS images in the full (0.3–8.0 keV), soft (0.3–1.0 keV), hard (4.0–8.0 keV), and very soft (0.3–0.5 keV) energy bands. Panel (a) is the same data as (b), but smoothed with a Gaussian kernel of \(\sigma = 3\) pixels. Panel (d) is the ChaRT MARX simulation for our observation, smoothed with the same Gaussian kernel. The gray-scale and contour levels of the ChaRT PSF were modified to approximately match panel (a). Contour levels for panels (a), (b), (c), and (e) start at 2, 16, 4, and 4 counts pixel\(^{-1}\), respectively, and increase by a factor of 2. Contour levels for the ChaRT PSF are irregular, to approximately match the contours in (a) and to further show the asymmetry of the PSF within \~2\arcsec, where our image is corrupted by pileup. Those levels are 15, 33, 80, 270, 2500, 18,000, 36,000, and 72,000 counts pixel\(^{-1}\). The FOV in each panel is 22\arcsec (3.3 kpc) square.

in Table 1) with 82 \pm 19 counts (from 15\arcsec to 25\arcsec), diffuse emission with 75 \pm 22 counts in region 6, from 15\arcsec to 30\arcsec, and an extended source nearer to the nucleus (region 7, 10\arcsec to 20\arcsec) with 74 \pm 24 counts.

We then constructed an image from our model PSF and subtracted it from the Chandra image to show the structure of these sources (see Fig. 6d). The 0.3–2.4 keV Chandra image was first smoothed with a Gaussian kernel of \(\sigma = 1.5\). The PSF was scaled by trial and error so that after subtraction, the net counts for extranuclear regions within \~2\arcsec were zero. This was done by examining radial and horizontal cuts across the image and ensuring that the pixel values in source-free regions far away from the nucleus fluctuated about 0.0 counts pixel\(^{-1}\). For comparison, we also show the (unsubtracted) 0.3–2.4 keV Chandra image in Figure 6b.

No excess emission was found from our radial profile analyses of the hard (2.4–8.0 keV) X-ray emission. While not enough counts were typically available in narrow energy bands, we did notice that the pointlike source in region 4 (source 7 in Table 1) was significantly harder than expected for thermal plasma emission with a \(kT\) of \~1 keV and a significant number of photons with \(E \geq 1.5\) keV. We list excess counts in several other energy bands in Table 2. Since the angular breaks that define our octants often pass through well-defined X-ray sources, we also list X-ray counts and 0.3–2.4 keV luminosities for the most well-defined clumps in the PSF-subtracted image. These sources are labeled e3a, e3b, e6, and e7 in Table 2, and their defining regions are shown in Figure 9. Those sources with an asterisk fall outside the angular range defined by their octants: for example, e7\* is primarily in octant 7 but also extends into octant 6.

3.2. Spectroscopy
3.2.1. Nuclear Source

We extracted a spectrum of the X-ray core from the CCD readout streak following a prescription from the Chandra calibration team (R. Smith 2004, private communication). We note here that the events in the readout streak do not suffer from CCD pileup. Source photons from the readout streak were taken from two thin rectangular regions extending \~0.75–4\arcsec above and below the nuclear source. Background counts were subtracted using four thin rectangular regions, one on each side of the readout streak. ARFs and RMFs were generated for a small circular region enclosing the X-ray core. The source spectrum was then
Fig. 6.—Extended X-ray emission in NGC 2992. (a) The six thin lines are the simulated 0.3–2.4 keV PSF from a ChaRT MARX simulation of a point source at the location of the NGC 2992 nucleus. Eight octants are labeled 1–8 in (b) and (d), and octants 2, 3, 4, 6, 7, and 8 are plotted with the following line types: dotted, short-dashed, long-dashed, dot–long-dashed, short-dash–long-dashed, and solid, respectively, in (a) and (c). The thick line is our best PSF, estimated from our Chandra data.

(b) Image (inverted linear gray scale) and contours of our 0.3–2.4 keV ACIS image, smoothed with a Gaussian kernel of $\sigma = 1.5$. Dashed circles are shown at radii spaced 10″ apart. The white contour level is 0.025 counts pixel$^{-1}$ (the background level), and black contours are $0.025(2^{N} + 1)$ counts pixel$^{-1}$, where $N \geq 1$. (c) Radial profiles of the 0.3–2.4 keV emission, showing an example of excess in octant 3 (dashed line) from $\sim 20''$ to $40''$ ($10^{1.3} - 10^{1.6}$). The thick black line is our best PSF (octants 2 and 8). The other five octants are shown without error bars, although the data have been binned to have $\geq 20$ counts bin$^{-1}$, and error bars for all octants are approximately the same. The line types for the octants are the same as for (a). Error bars are Poissonian ($\sqrt{N}$). (d) PSF-subtracted 0.3–2.4 keV ACIS image. The (inverted) gray-scale image is shown with the same linear stretch as in (b), and the dashed circles are the same as for (b). The white contour is $-0.05$ counts pixel$^{-1}$, and the black contours are 0.05, 0.1, 0.2, 0.4, and 0.8 counts pixel$^{-1}$. One pixel is $0''.492$ in (b) and (d). Panels (b) and (d) have a FOV of $2''23 \times 2''45$ (23.3 kpc $\times$ 21.2 kpc).
### TABLE 2

**Kiloparsec-Scale Extended Soft X-Ray Emission near NGC 2992**

| Octant/RANGE (arcsec) | Source Name | COUNTS IN ENERGY BAND | Notes |
|-----------------------|-------------|-----------------------|-------|
|                       |             | 0.3–1.0 keV (1)       |       |
|                       |             | 1.0–1.5 keV (2)       |       |
|                       |             | 0.3–1.5 keV (3)       |       |
|                       |             | 1.5–2.4 keV (4)       |       |
|                       |             | 0.3–2.4 keV (5)       |       |
|                       |             | 2.4–8.0 keV (6)       |       |
|                       |             | L_X(0.3–8.0 keV) (7)  |       |
|                       |             | NOTES (8)             |       |
| 1.......................| ...         | ...                   | ...   |
| 2.......................| ...         | ...                   | ...   |
| 3/20°–40°................| e3          | <22                   | 26 ± 12 |
|                       |             | 45 ± 15               | 43 ± 15 |
|                       |             | 90 ± 22               | <74    |
| 4/15°–25°..............| Sec7        | 17 ± 7                | 23 ± 11 |
|                       |             | 51 ± 13               | 35 ± 14 |
|                       |             | 82 ± 19               | <60    |
| 5.......................| ...         | ...                   | ...   |
| 6/15°–30°..............| e6          | <24                   | <35    |
|                       |             | <44                   | 57 ± 16 |
|                       |             | 75 ± 22               | <70    |
| 7/10°–20°..............| e7          | 42 ± 12               | <40    |
|                       |             | 64 ± 18               | <49    |
|                       |             | 74 ± 24               | <72    |
| 8.......................| ...         | ...                   | ...   |
|                       | e3a*        | ...                   | ...   |
|                       | e3b         | ...                   | ...   |
|                       | e6*         | ...                   | ...   |
|                       | e7*         | ...                   | ...   |

**Notes.**—Excess net X-ray counts in various energy bands, using our best PSF, which was generated from regions 2 and 8 (see Fig. 3). For reference, at 32.5 Mpc, 10° is 1.58 kpc. Only regions with significant (>2σ) excess counts in one of the bands are reported here, where σ is the sum (in quadrature) of the Poisson errors (\(\sqrt{N}\)) of the net counts for the given region from the data and from the PSF. Upper limits are given as 3σ. For reference, the exposure time is 49.5 ks. **Col. (1):** Octant (see Fig. 3) and radial range. **Col. (2):** Source name. **Cols. (3)–(8):** Counts in ACIS energy bands. **Col. (9):** Full-band (observed/absorbed) X-ray luminosity in units of log ergs s⁻¹, scaled from the 0.3–2.4 keV count rate, assuming a bremsstrahlung emission model with \(kT = 0.5\) keV and the Galactic absorption column, \(5.26 \times 10^{20}\) cm⁻². To convert observed 0.3–8.0 keV X-ray luminosities to observed luminosities in the ROSAT (0.2–2.4 keV) band, multiply by 1.02. **Col. (10):** Additional notes.
grouped so that it had a minimum of 20 counts per spectral bin. Since the fraction of the total counts that are detected in the streak is not well calibrated, the absolute normalization obtained from spectral fitting is not useful. However, the shape of the spectrum is very useful.

By restricting the energy range to 0.3–8.0 keV, we obtain a spectrum with 6744 source counts. We use XSPEC version 11.3.0 for spectral fitting. An external hydrogen column was fixed at the Galactic value of 5.26 × 10^{20} cm^{−2} (Dickey & Lockman 1990). An additional intrinsic hydrogen column was allowed to vary during the fitting. With a simple absorbed power-law model, we obtain a very good fit ($\chi^2$/dof = 197.0/205), with a power-law model with $\Gamma = 1.86 \pm 0.08$ and $N_H = (0.71 \pm 0.05) \times 10^{22}$ cm$^{-2}$. Adding a neutral ($E = 6.4$ keV) Fe Kα line as a Gaussian line only improves the fit by $\Delta \chi^2 = 0.2$.

This power-law slope is consistent with the 1997–1998 large-aperture BeppoSAX spectrum ($\Gamma \approx 1.7$; Gilli et al. 2000) but is not consistent with the much flatter ASCA spectrum taken in 1994 ($\Gamma \approx 1.2$; Weaver et al. 1996). Photon indices of $\Gamma \approx 1.9$ are typical in one Seyfert nuclei (e.g., Nandra & Pounds 1994; Nandra et al. 1997), where the X-ray AGN is viewed directly. Since we know that the X-ray core spectrum comes from a very small region (≈1–2 pixels across (≈75–150 pc) and its spectrum is not consistent with Compton reflection, we conclude that it must be either emission directly from the AGN, as in type 1 Seyfert galaxies, or gray scattering of the AGN emission from electrons within ~150 pc (≈10$^6$) of the AGN. In §3.2.2, we assume that the direct spectrum of the AGN is given by the streak spectrum and use this to constrain the AGN component of the spectrum within ~3 kpc of the nucleus.

3.2.2. Near-nuclear X-Ray Emission

Using the ACISISSPEC CIAO tool, we extracted a spectrum of the X-ray emission within a radius of 18" (2.8 kpc) centered on the X-ray core (see §3.1.2). We excluded the very central region (with piled events) by rejecting all events within the “middle” ellipse in Figure 4c (with semimajor and semiminor axes of 3.4 and 2.7, respectively). We also excluded events from a faint point source (source 7 in Table 1) and from a thin rectangular region enclosing the CCD readout streak. This emission region thus includes a fraction of the X-ray core (§3.1.2), all of source SE (§3.1.3), some of the emission from extended sources e6 and e7 (§3.1.4), and the accumulation of any other undetected extended X-ray sources within 2.8 kpc of the nucleus. Background counts were taken from four remote source-free rectangular regions adjacent to the nuclear region. The ≈14,600 count 0.3–8.0 keV source spectrum was binned to >20 counts bin$^{-1}$ and was analyzed with XSPEC. We list the results from spectral fitting in Table 3. All models include an additional neutral hydrogen absorption component, fixed at 5.26 × 10^{20} cm^{−2} (Galactic value from Dickey & Lockman [1990]). Since much of the emission from the AGN point source has been rejected due to pileup and much of the remaining emission has been omitted by our extraction region, the absolute fluxes we obtain from the AGN spectral components are not useful for comparison with previous results (e.g., ASCA).

The near-nuclear spectrum is fairly well fitted ($\chi^2 = 1.13$) by a shallow ($\Gamma \approx 0.9$) absorbed power law. However, since some of the photons in the source region are from the PSF wings of the X-ray core ($\Gamma = 1.86$; §3.2.1), we must reject this simple model.

We thus included a power-law component with the slope fixed at $\Gamma = 1.86$, which was the value determined from the spectrum of the CCD readout streak (i.e., 1 or 2 pixels from the X-ray core). Since the PSF wings from the X-ray core contribute to our near-nuclear region ($r > 18''$), a $\Gamma = 1.86$ power-law component should be present. The absolute normalization of the steep spectrum is not well calibrated (R. Smith 2004, private communication), so we left the normalization to the $\Gamma = 1.86$ power-law free while fitting. We did not correct for the difference in the PSF wings for soft and hard energies (e.g., Allen et al. 2004), but we note that the PSF wings are quite similar for energies ~4.0–8.0 keV, and this is the energy range in which most of the events from the power-law component reside.

A simple absorbed power law, with $\Gamma$ and $N_H$ fixed at the same values as for the X-ray core, is a very poor fit ($\chi^2 \approx 3.7$). However, if a second absorbed power law is added (partial covering), a good fit ($\chi^2 = 1.05$; $\chi^2$/ν = 372/354) is obtained, with $\Gamma \approx 0.5$ and $N_H \sim 10^{20}$ cm$^{-2}$ for the second component. In this model, the flat power-law component has an observed 0.3–8.0 keV flux ~2.5 times that of the first (AGN) component. While we do not view this partial covering model as physically reasonable, it does show the importance of components other than direct or electron-scattered AGN emission.

If the second component is replaced with a MEKAL thermal plasma model, the fit is very poor: $\chi^2 = 2.8$ for either fixed (solar) or variable abundances (best fit at Z ≈ 0.1 Z$_\odot$). We next tried a cold reflection model (PEXRAV) for the second component, fixing the input power-law spectrum at $\Gamma = 1.86$. This is again a fairly good fit ($\chi^2 = 1.18$), although it is still significantly poorer than the partial covering model, with a $\Delta \chi^2$ of 37.

Adding a third component to the fit (a MEKAL thermal plasma model) significantly improves the fit ($\chi^2 = 1.03$). Our best-fit model (PL+PEXRAV+MEKAL; see Table 3, model 3b) is obtained for a low-abundance plasma with kT ≈ 0.5 keV and Z ≈ 0.01 Z$_\odot$. Note that the best-fit PEXRAV components are almost completely reflection-dominated; i.e., they have very large R-values. We discuss the issue of low abundances further in §4.2.3. Compared with the partial covering model, $\chi^2$ is lower for this model by a difference of 10. We take model 3b as our best model and measure observed 0.3–8.0 keV luminosities of $2.3 \times 10^{40}$ ergs s$^{-1}$ for the reflected component and $1.4 \times 10^{40}$ ergs s$^{-1}$ for the “thermal” component. In Figure 7 we show the near-nuclear spectrum, together with the various model components.

We find no evidence for an Fe K line in the near-nuclear spectrum. If we add in a Gaussian line fixed at 6.4 keV to models 1a and 1b (fixed PL models) or our best-fit model (3b), an equivalent width ~50 eV line is best fitted, but $\Delta \chi^2 \leq 1$. Although our proposed reflection component in the near-nuclear spectrum may well produce a strong Fe K line, there is also significant direct AGN emission in the composite spectrum. For example, for our best-fit model (3b), ~50% of the 0.3–8.0 keV flux comes from the direct (PL) component (see Table 3). Thus, any Fe K line emission produced by cold Compton reflection may just be washed out. To test this hypothesis, we used a simple PEXRAV model with $\Gamma = 1.86$ for the AGN component and added a narrow Gaussian line fixed at 6.4 keV. The fit was quite reasonable ($\chi^2 = 378.1$) compared with other models in Table 3. The best-fit value of $R$ was 15.87. The Gaussian line was best fitted with an equivalent width of 24 eV and an upper limit ($\Delta \chi^2 = 2.7$) of 674 eV. If only the reflection component is allowed by the PEXRAV model, the equivalent width increases by a factor of 1.63. Therefore, the upper limit one would expect if the direct component was not present is ~1.1 keV, which is more consistent with a reflection-dominated X-ray spectrum.
| Model No. (1) | Model Description (2) | $\chi^2$ (3) | $\chi^2$/dof (4) | $L_X^{\text{obs}}$ (log cgs) (5) | $L_X^{\text{unabs}}$ (log cgs) (6) | $\Gamma$/kT (7) | $N_H$ (10$^{22}$ cm$^{-2}$) (8) | Norm (10$^{-4}$) (9) | Additional Notes (10) |
|---|---|---|---|---|---|---|---|---|---|
| 1a | PL | 1.13 | 401.1/355 | 41.55 | -11.29 | $\Gamma = 0.91 \pm 0.02$ | 0.19 $\pm 0.04$ | 3.21$^{+0.17}_{-0.15}$ |
| 1b | PL (fixed) | 3.74 | 1331.6/356 | 41.70 | -11.36 | $\Gamma = 1.86 f$ | 0.73 | 9.33 |
| 2a | PL+PL (Part Cov) | 1.05 | 371.7/354 | 41.16 | -11.68 | $\Gamma_1 = 1.86 f$ | 0.71f | 3.71$^{+0.40}_{-0.30}$ |
| 2b | PL+PEXRAV | 1.18 | 419.0/354 | 41.37 | -11.47 | $\Gamma = 1.86 f$ | 0.71f | 5.93 $\pm 0.33$ |
| 2c | PL+MEKAL VarAb | 2.82 | 997.4/354 | 41.54 | -11.30 | $\Gamma = 1.86 f$ | 0.71f | 8.99 |
| 2d | PL+MEKAL VarAb | 2.80 | 989.6/353 | 41.54 | -11.30 | $kT = 0.25$ | 0 | 0.36 |
| 3a | PL+PEXRAV+MEKAL VarAb | 1.11 | 390.0/351 | 39.86 | -13.06 | $kT = 0.27$ | 0 | 2.25 |
| 3b | PL+PEXRAV+MEKAL VarAb | 1.03 | 361.4/350 | 39.66 | -13.21 | $kT = 0.31^{+0.04}_{-0.03}$ | 0.04 $\pm 0.08$ | 0.27$^{+0.30}_{-0.11}$ |

Notes.—See § 3.2.2 for description of the “near-nuclear” region used to extract the spectrum. All fits include an additional Galactic hydrogen absorption column of 5.26 $\times$ 10$^{20}$ cm$^{-2}$ (Dickey & Lockman 1990). The letter “f” after the value indicates that the parameter was fixed at that value during the fit. XSPEC parameter errors were not computed for poorly fit models 1b, 2c, and 2d, all of which had $\chi^2 > 2.5$. All errors are given for 90% confidence for one interesting parameter ($\Delta \chi^2 = 2.7$). Col. (1): Model number. Col. (2): Description of XSPEC model (PL, power law; PEXRAV, cold reflection of a PL spectrum; MEKAL, thermal plasma; VarAb, nonsolar variable abundance). Cols. (3) and (4): Reduced $\chi^2$ value $\chi^2 = \chi^2 / \nu$, where $\nu$ is the number of degrees of freedom (dof). Col. (5): Logarithm of the observed 0.3–8.0 keV X-ray luminosity of the component in ergs s$^{-1}$ (assuming $D = 32.5$ Mpc). Col. (6): Logarithm of the unabsorbed 0.3–8.0 keV X-ray flux of the components. All $N_H$ values were zeroed. Col. (7): Photon index $\Gamma$ for PL and PEXRAV models, and MEKAL plasma temperature in keV. Col. (8): Intrinsic hydrogen absorption column of model component, in units of 10$^{22}$ cm$^{-2}$. Col. (9): XSPEC model normalization. For the PL and PEXRAV models, the units are photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$ at 1 keV. For the PEXRAV model, the normalization is for the direct component only. For the MEKAL model, the units are 10$^{-14}$ (4$\pi D^2$) / $\int n_e (m_1)$ / cm$^{-3}$ / dV, where $D$ is the distance to the X-ray source in centimeters. Col. (10): Additional notes on component parameters. The quantity $R$ is the reflection scaling factor for the PEXRAV model. The $e$-folding energy for the PEXRAV model was fixed at 100 keV.
3.3. Properties of the Soft Excess Emission

As mentioned in § 3.1.4, the extended X-ray sources e6 and e7 with net 0.3–8.0 keV luminosity $L_X = 1.2 \times 10^{39}$ ergs s$^{-1}$ (Table 2) comprise part ($\sim 10\%$) of the thermal soft excess ($L_X \approx 1.4 \times 10^{40}$ ergs s$^{-1}$), as does the source SE, with $L_X \sim 1-2 \times 10^{39}$ ergs s$^{-1}$ (§ 3.1.3). It is quite possible that the unaccounted ($\sim 75\%–80\%$) soft excess emission could be explained by undetected or unresolved hot, extranuclear gas clouds, although diagnosing this with the existing ACIS data is not very practical, due to the strong X-ray core and uncertainties in the PSF. Since the AGN core spectrum extracted from the readout streak does not show any evidence for soft excess, an alternative explanation is that the unaccounted soft excess originates from very luminous ($L_X \sim 10^{40}$ ergs s$^{-1}$) EXRs in the region between $\sim 1''$ and $2.5''$. A fraction of these photons would then be repositioned to larger radii by the *Chandra* PSF and so would have been included in our near-nuclear spectrum ($r \geq 3''$).

4. DISCUSSION

As we have shown, we detect $\sim 2-3 \times 10^{39}$ erg s$^{-1}$ of extended soft X-ray emission in NGC 2992 and find evidence for $\sim 1 \times 10^{40}$ ergs s$^{-1}$ in a “low-abundance thermal” spectral component. The AGN nucleus ($r \leq 1''$) is well fitted by a power law, but a larger aperture spectrum of the near-nuclear region requires a significant cold reflection component. In this section, we discuss possible scenarios for the emission processes producing the X-ray emission from the nuclear source, the extended sources e3, e6, e7, and SE, and the soft excess.

4.1. The Nuclear Point Source

Large-aperture 2.5 *ASCA* observations of the X-ray nucleus in 1994 by Weaver et al. (1996) yielded similar observational results to our near-nuclear model 1a (i.e., when both data sets are modeled with a simple absorbed power law; $\Gamma \sim 1$ and $N_H \sim 2 \times 10^{21}$ cm$^{-2}$). This observational model is obviously an inadequate description of the emission components, but it shows general similarity in the spectral shape. Weaver et al. model the *ASCA* spectrum with both Compton reflection and gray scattering (partial covering model) of a $\Gamma = 1.7$ nuclear source that was hidden behind an absorbing column of $\sim 10^{22}$ cm$^{-2}$. However, *BeppoSAX* observations in 1997 and 1998 with a similar aperture were well fitted by a simple power-law model with $\Gamma \approx 1.7$ and $N_H \approx 10^{22}$ cm$^{-2}$ (Gilli et al. 2000). Thus, as shown by Weaver et al. (1996), the cold (Compton) reflection component is historically variable on the scale of a few years.

The fact that we do not see evidence for cold reflection in the nuclear streak spectrum but we do see evidence for it in the near-nuclear ($r \geq 3''$) spectrum implies that the reflection region is located outside of the $1-2$ pixels that are clocked along the readout streak. Thus, we argue that the cold reflection region is located at radii $r \geq 0.5-1.70$, or $r \geq 75-150$ pc.

We show the positions of the X-ray core in optical and radio images of the nuclear region in Figure 8. The $I$-band, $H_\alpha$, and...
[O \text{iii}] peaks (see Figs. 8a, 8b, and 8d, respectively) are displaced from the X-ray core position by 1''–2'' to the northwest. This displacement could be an obscuration effect, or it could be due to alignment uncertainties between the optical and X-ray frame. Unfortunately, CCD pileup prevents reliable imaging of any of the ACIS X-ray emission near the peak of the northwest “ionization cone” (i.e., the northwest H\text{\alpha} and [O \text{iii}] peak), and we cannot diagnose if there is another X-ray source there, such as the cold reflector. Veilleux et al. (2001) and Garcia-Lorenzo et al. (2001) find that the stellar kinematic center is positioned \approx1'' southwest of the [O \text{iii}] peak. Thus, the supermassive black hole, as marked by the X-ray and radio core, may not yet have settled into the center of the galaxy. However, since gas motions are quite complex in the center of NGC 2992 (e.g., Veilleux et al. 2001) and the galaxy disk is viewed nearly edge-on, perhaps the X-ray/kinematic center displacement is consistent with uncertainties in modeling the optical data.

The X-ray core is, however, coincident with the 6 cm radio core—the apex of the two diffuse “radio bubbles,” a.k.a. “figures of eight” (see Fig. 8c). This suggests that the radio bubbles may be inflated by the AGN (e.g., Wehrle & Morris 1988) and not a starburst, since NIR observations suggest that the youngest
star-forming region is located in the dust lane (Chapman et al. 2000), a few arcseconds northwest of the X-ray core and the radio core.

4.2. Extended X-Ray Emission and Soft Excess

4.2.1. Near-nuclear X-Ray Sources

The diffuse soft X-ray emission within 5″ is displayed against the optical and radio emission in Figure 8. The SE X-ray source, which has a centroid along PA $\sim 160°$, is coincident with the southeast radio bubble, but there is no luminous optical line or continuum emission there. It is thus possible that the X-rays from the SE source are collisionally excited emission produced by outflowing gas in the bubble. The apparent low abundance of this X-ray gas is discussed in § 4.2.3.

Allen et al. (1999) and Veilleux et al. (2001) find very high velocities for the ENLR gas in the southeast cone, as high as 670 km s$^{-1}$ (Allen et al. 1999). Shock-model fits to the emission-line ratios from that region imply shock velocities of $\sim 300$–500 km s$^{-1}$ (Allen et al. 1999). A shock velocity of 500 km s$^{-1}$ produces thermal X-rays with temperature $\sim 0.3$ keV, which is certainly consistent with the results from our spectral fitting ($kT = 0.3$–0.8 keV; Table 3, model 3b).

On the basis of kinematic modeling of the H$\alpha$-emitting gas, Veilleux et al. (2001) estimate a kinetic energy luminosity of $L_{KE} \approx 10^{40} (n_e/100$ cm$^{-3})^{-1}$ ergs s$^{-1}$. Starburst-driven winds yield X-ray luminosities of $\sim 0.03 L_{KE}$ (e.g., Strickland 2004), implying $\sim 3 \times 10^{38}$ ergs s$^{-1}$ of soft X-rays from the nuclear outflow in NGC 2992. This is an order of magnitude lower than $L_X$ of the SE X-ray source; however, since $L_X \propto n_e^4 \phi$, where $n_e$ is the electron density and $\phi$ is the volume filling factor, it is possible that the physical conditions in the southeastern region could produce a significantly larger X-ray luminosity in NGC 2992.

Compared with typical ENLR gas, the hot X-ray–emitting gas is quite tenuous. Assuming a 0.2–2.4 keV emissivity of $10^{-22.4}$ ergs cm$^{-3}$ s$^{-1}$ (Suchkov et al. 1994), we derive gas densities $n \sim \phi_X^{1/2} (0.3$–2$) \times 10^{-2} \text{ cm}^{-3}$ for the four well-defined X-ray sources in Table 2 (e3a, e3b, e6, and e7; see Colbert et al. [1998] for a detailed description of similar calculations). Here $\phi_X$ is the volume filling factor of the X-ray–emitting gas and is distinct from $\phi$ for the optical line–emitting gas. ENLR clouds have much larger electron densities: $\sim 10^{-2}$–$10^4$ cm$^{-3}$ (e.g., Robinson 1989, 1994). The implied pressure $p = 2 n_kT$ of the X-ray gas, assuming $kT = 0.5$ keV (as in Table 2), is $p \sim \phi_X^{1/2} (0.5$–3$) \times 10^{-11}$ dyne cm$^{-2}$, which is reasonably close to $n_kT$ of ENLR clouds, suggesting that there may be pressure equilibrium between the two gas phases. The cooling time of the X-ray gas can also be estimated (e.g., Colbert et al. 1998), and we find $t_{cool} \sim \phi_X^{1/2} (3$–20$) \times 10^8$ yr.

4.2.2. Kiloparsec-Scale X-Ray Sources

As mentioned in § 3.1.4, we find three diffuse extranuclear X-ray sources (e3, e6, and e7), each with $L_X \approx 6 \times 10^{38}$ ergs s$^{-1}$ (Table 2). These sources are located at larger distances ($r = 10''$–40″, or 1.6–6.3 kpc; see Fig. 6d). In Figure 9, we show the relative positions of these sources with respect to the kiloparsec-scale optical and radio emission. We also label the well-defined X-ray clumps in the image as e3a, e3b, e6, and e7 (see § 3.1.4).

A kiloparsec-scale 20 cm radio “arm” extends eastward from the nucleus in the same position angle as source e3 and reaches the inner part of this X-ray source. Thus, both could be generated by a kiloparsec-scale nuclear outflow. Source e3 is also positioned within the opening angle of the southeast ionization cone (see Fig. 9d), and thus AGN photoionization is also a possible emission mechanism.

4.2.3. Soft Excess

As summarized by Ogle et al. (2003), many of the extended X-ray sources found in Seyfert galaxies are well modeled with pure photoionization and photoexcitation models—collisional excitation is not required. The characteristic observational spectral signature of soft excess in non-grating Chandra and XMM-Newton observations is a one- or two-temperature thermal model with near-zero abundances (e.g., Bianchi et al. 2003; Schuch et al. 2002; Done et al. 2003), which is precisely the same as our results for NGC 2992. The spectra of the brightest extranuclear X-ray nebulae in NGC 1068 and NGC 4151 are well fitted by AGN photoionization and photoexcitation models, with no need for collisional excitation (e.g., Sako et al. 2002; Sambruna et al. 2001; Kinkhabwala et al. 2002; Ogle et al. 2003). However, the exact same “low-abundance” phenomenon occurs for X-ray emission from starburst-driven superwinds when they are fitted with a one-temperature thermal model (e.g., Ptak et al. 1997). A high-quality grating spectra of the starburst galaxy M82 is much better represented with multi-temperature abundances (Read & Stevens 2002). Strickland et al. (2004a, 2004b) find that a physically reasonable solution for Chandra CCD (non-grating) spectra of superwinds is a two-temperature model with low Fe abundances. Thus, the low metallicity implied by our simple single-temperature thermal plasma component (e.g., model 3b, Table 3) does not necessarily imply that the soft excess (which includes sources e3, e6, e7, and SE) is produced solely (or even partially) by AGN photoionization. The result is ambiguous.

4.3. AGN-driven Outflow versus Starburst-driven Outflow

Does NGC 2992 have a nuclear starburst that could indeed power a galactic wind? It has a total FIR luminosity of $7 \times 10^{43}$ ergs s$^{-1}$ (Moshir et al. 1997), which suggests a star formation rate (SFR) of $\approx 4 M_\odot$ yr$^{-1}$, assuming that the FIR emission from the AGN can be neglected and the SFR $= 5.7 \times 10^{-4} L_{\text{FIR}}$ (e.g., Colbert et al. 2004). The Infrared Astronomical Satellite (IRAS) colors of NGC 2992 are more similar to those of starbursts than to “pure” (not composite starburst-Seyfert) Seyfert galaxies (e.g., Colbert 1997). Strickland et al. (2004b) show empirically that X-ray halo emission from a starburst $L_{\text{halo}} \approx (4 \times 10^{39}$ ergs s$^{-1}$) soft X-rays from the hypothetical $4 M_\odot$ yr$^{-1}$ starburst. On the basis of the range in $L_{\text{halo}}/L_{\text{FIR}}$ for the starburst galaxies studied by Strickland et al. (2004b), the starburst wind component can be as much as a factor of 2 more: $L_{\text{wind}} \approx 6 \times 10^{39}$ ergs s$^{-1}$. This is certainly consistent with the 20%–25% of the soft excess that we image with Chandra ($L_X^{\text{net}} \approx 3$–4 $\times 10^{39}$ ergs s$^{-1}$ from sources e3, e6, e7, and SE).

However, detecting a nuclear starburst in NGC 2992 is difficult, due to heavy obscuration and the bright X-ray AGN. It is quite possible that the outflow (and thus the extranuclear X-ray sources) may be energized by the AGN instead. Soifer et al. (2004) find that $\approx 50\%$ of the 12 $\mu$m IRAS emission from NGC 2992 is positioned within 0′34 (50 pc) and conclude that this compact 10 $\mu$m emission is produced by an AGN instead of by a nuclear starburst. It is not clear, however, if this is also true of the higher wavelength IRAS fluxes (e.g., 60 and 100 $\mu$m), which are usually used to estimate the star formation rate of the putative starburst. The FIR/radio flux ratio $\mu$ for NGC 2992 is quite low (2.09), compared with starburst galaxies, for which $\mu$ clusters tightly (near 2.5, e.g., Colbert et al. 1996a), suggesting significant
AGN radio emission. Thus, the radio loops may be more consistently explained by an AGN-driven outflow. Chapman et al. (2000) do, however, find very red \((R - H)\) as high as 4.8) “starburst” regions within ~1” of the NIR core in the dust lane. Hence, it is possible that a strong starburst does exist but remains hidden behind the dust lane (e.g., see \(V\)-band image in Figs. 8a and 9c).

It is certainly possible that AGN photoionization could be powering the 75%–80% of the soft excess that was not imaged in our Chandra observations. For example, this emission could be positioned closer \((r \leq 5’’)\) to the AGN and would thus be invisible in the Chandra image due to pileup effects and/or the tremendous intensity of the AGN X-ray core.

We are grateful to Randall Smith, Tahir Yaqoob, Steve Kraemer, and Patrick Ogle for helpful discussions and to B. García-Lorenzo, M. Allen, and P. Shopbell for providing images and data analysis tools. We thank the anonymous referee for helpful suggestions. E. J. M. C. acknowledges support from NASA for SAO grant GO3-4116X.
