CHANDRA X-RAY OBSERVATIONS OF NGC 4151

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ABSTRACT

We present Chandra X-ray observations of the nearby Seyfert 1.5 galaxy NGC 4151. The images show the extended soft X-ray emission on the several hundreds of parsec scale with better sensitivity than previously obtained. We show that the hard X-ray component (greater than 2 keV) is spatially unresolved. The spectrum of the unresolved nuclear source may be described by a heavily absorbed ($N_H \approx 3 \times 10^{22} \text{ cm}^{-3}$), high power law ($\Gamma \approx 0.3$) plus soft emission from either a power-law ($\Gamma \approx 2.6$) or a thermal ($kT \approx 0.6 \text{ keV}$) component. The flux of the high-energy component has decreased from that observed by ASCA in 1993, and the spectrum is much harder ($\Gamma \approx 0.3$ in 2000 vs. $\Gamma \approx 1.5$ in 1993). The large difference between the soft and hard spectral shapes does not favor the partial covering or scattering model of the “soft excess.” Instead, it is likely that the hard and soft nuclear components represent intrinsically different X-ray sources. The stronger nuclear emission lines of those seen by the Chandra HETGS spectrum are detected. Spectra of the extended emission to almost 1 kpc northeast and southwest of the nucleus have also been obtained. The spectra of these regions may be described by either thermal bremsstrahlung ($kT \approx 0.4-0.7 \text{ keV}$) or power-law ($\Gamma \approx 2.5-3.2$) continua plus three emission lines. There is an excellent correlation between the extended X-ray and [O III] $\lambda 5007$ line emissions. We discuss the nature of the extended X-ray emission. Because there is no extended electron-scattered hard X-ray emission, an upper limit to the electron scattering column can be obtained. This upper limit is much too low for the soft X-rays to be electron-scattered nuclear radiation, unless the nucleus radiates soft X-rays much more strongly toward the extended regions than toward Earth, a situation we consider unlikely. We favor a picture in which the extended X-ray-emitting gas is heated in situ by the nuclear radiation. Some of the X-rays may originate from a hot phase that confines the warm ionized gas seen optically, although X-ray emission produced via photoionization by the nucleus is also likely. A faint, probably background, compact X-ray source lies $\sim 22$ from the nucleus to the southwest, approximately along an extension of the extended southwest X-ray and [O III] emission.

Subject headings: galaxies: active — galaxies: individual (NGC 4151) — galaxies: ISM — galaxies: nuclei — galaxies: Seyfert — X-rays: galaxies

1. INTRODUCTION

Because of its proximity (13.2 Mpc for $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, 1" = 64 pc), the Seyfert 1.5 galaxy (Osterbrock & Kozi 1976) NGC 4151 is one of the best studied among the class. X-ray observations show that NGC 4151 is a modest luminosity ($L_{2-10\text{ keV}} \approx 2-20 \times 10^{42} \text{ ergs}^{-1}$) active galactic nucleus (AGN) with a highly variable and hard continuum. There is evidence for a spectral-flux correlation above 2 keV (Perola et al. 1986; Yaqoob & Warwick 1991; Yaqoob et al. 1993). The soft X-ray continuum of NGC 4151 is characterized by a prominent excess of X-ray emission above an extrapolation of the absorbed, higher energy power-law component to lower energies. This “soft excess” has been described in terms of partial covering, a warm absorber, scattered nuclear radiation, and additional spectral components (e.g., Holt et al. 1980; Yaqoob & Warwick 1991; Weaver et al. 1994a, 1994b).

Einstein and ROSAT observations identified extended soft X-ray emission that appears to be associated with ionized gas visible optically (Elvis, Briel, & Henry 1983; Morse et al. 1995). This extended emission must account for at least part of the “soft excess.” Ogle et al. (2000) have recently obtained a 48 ks observation of NGC 4151 with the High Energy Transmission Grating Spectrometer (HETGS) on board the Chandra X-Ray Observatory. Their observation provided the first high-resolution X-ray spectroscopy of NGC 4151 and also a zero-order image. Strong, narrow X-ray emission lines are seen in the spectrum. Evidence of both photoionized and collisionally ionized gas was found. However, their zero-order image has only modest signal-to-noise ratio as a result of the limited transmission of the gratings.

We thought it worthwhile to obtain an exposure without the gratings in place in order to obtain a sensitive image of the extended emission. Given the dependence of the HETGS zero-order transparency on energy, our $\sim 30$ ks direct image has higher sensitivity than the zero-order image by Ogle et al. (2000) for all energies below $\approx 6 \text{ keV}$.

In this paper we present a Chandra Advanced CCD Imaging Spectrometer (ACIS) observation of NGC 4151. Observations are described in § 2. Data analysis and results are presented in § 3, where we present the best X-ray image of NGC 4151 to date and low-resolution spectra of both the nucleus and extended regions. The X-ray image is also compared with optical and radio images. Implications of the observation are discussed in § 4. The detection of a

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The observations of NGC 4151 were obtained in two phases. First, to evaluate the effects of pileup in the bright inner regions of NGC 4151, we took a preliminary 4.3 ks observation on 1999 December 4 in so-called alternating mode, in which single exposures with a 0.1 s frame time were alternated with two exposures with a 0.4 s frame time. The observation showed that the nucleus is significantly piled up in the 0.4 s, but not in the 0.1 s, frame time observations. We also inferred that the bright inner regions of the galaxy would be strongly affected by pileup in the planned long exposure, which would use the standard 3.2 s frame time. We thus decided to obtain another, longer observation in “alternating mode,” in addition to the long observation, to mitigate the effect of pileup in the inner regions. Therefore, the second phase of observations consisted of an \( \approx 26 \) ks observation with 3.2 s frame time and an \( \approx 7 \) ks observation in “alternating mode,” including both 0.1 and 0.4 s exposures. Observations are summarized in Table 1. In the \( \approx 26 \) ks observation, CCDs I2, I3, S1, S2, S3, and S4 were read out, though all of the detected X-ray emission from NGC 4151 is on S3. In both “alternating mode” exposures, only chip S3 was read out.

The fraction of bad grades (i.e., the ratio of the number of counts with ASCA grades 1 + 5 + 7 [defined in the Chandra Proposers’ Observatory Guide 2000] to the total number of counts) was found to be a good indicator of the degree of pileup in any given pixel through comparison with the event rates in the different frame time observations. Regions with a large fraction (nominal value greater than 10\%) of bad grades were considered to be piled up. As already found in the preliminary observation, the 0.1 s frame time data were not piled up, with less than 6\% of the grades in the brightest pixel being bad. The 0.4 and 3.2 s frame time data were found to suffer from pileup out to 1’3 and 3’ from the nucleus, respectively.

All of the analysis was initially done with the “old” response functions (“fes”), and data were reduced and analyzed with CIAO v1.1.5 and XSPEC v11.0.1. The observations were screened for high background count rates and aspect errors by following the Chandra Science Threads. After we received the referee’s report, new versions of the response function (CALDB 2.7) were available. We reanalyzed some of the data with these new response functions and with the latest version of CIAO v2.1.2. In general, the change in derived parameters (such as absorbing column, photon index, bremsstrahlung temperature, and emission-line properties) was small. We did not reanalyze the 0.1 s frame time nuclear observations with the new response functions because our results agree well with the concurrent HETGS observations of the nucleus by Ogle et al. (2000), which have much higher spectral resolution and are thus superior for detection of lines. We have, however, added 0.2 keV to the line energies below 1 keV from the 0.1 s frame time observation since there is a systematic error of this magnitude when using the old response functions. The results presented for the 0.4 s frame time nuclear observations and the 3.2 s frame time observations of the extended emission employed the new response functions.

3. DATA ANALYSIS AND RESULTS

3.1. Morphology of X-Ray Emission

The soft X-ray (0.3–2.5 keV) images derived from the 0.1, 0.4, and 3.2 s frame time exposures are shown in Figure 1. The “hole” at the position of the nucleus in the 3.2 s frame time image (Fig. 1c) is due to pileup. The X-ray emission of NGC 4151 comprises a bright unresolved nucleus and resolved extended regions. The southwest part of the extended emission extends as far as 14’ (\( \approx 900 \) pc) from the nucleus along P.A. \( \approx 233 \). The northeast part of the extended emission extends to \( \approx 700 \) pc from the nucleus along P.A. \( \approx 75 \). The structure of the extended emission appears to be knotty rather than smooth. A moderately bright, compact knot is clearly visible 6’ (\( \approx 380 \) pc) southwest of the nucleus (Fig. 1c). A contour map representation of the extended emission is shown in Figure 2. Our images are in good agreement with the HETGS zero-order image obtained by Ogle et al. (2000) but are more sensitive.

The 2–9 keV emission is not resolved in our observations, as can be seen by comparing the radial profile of the observations in this band with the point spread function (PSF). In Figure 3a, the 5.5 keV model PSF without aspect error is plotted with the observed profiles of the 2–9 keV emission. The 0.4–2 keV emission is, on the other hand, resolved along the northeast-southwest direction but is not (or is marginally) resolved along the northwest-southeast direction (Figs. 3b, 3c, and 3d).

3.2. X-Ray Spectra of the Nuclear Region

We extracted spectra of the nucleus from a circular region with radius 3’ in the 0.1 and 0.4 s frame time observations. The total number of counts in the spectra are 2033 and

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**TABLE 1**

**Observation Summary**

| Obs ID | Sequence Number | Observation Date | Frame Time | Exposure* |
|--------|-----------------|------------------|------------|-----------|
| 347..... | 700019 | 1999 Dec 04 11:29:54 | 0.1 | 296.8 |
| 347..... | 700019 | 1999 Dec 04 11:29:54 | 0.4 | 2374.3 |
| 348..... | 700020 | 2000 Mar 15 10:51:40 | 3.2 | 26.2b |
| 372..... | 700198 | 2000 Mar 06 13:27:39 | 0.1 | 771.1 |
| 372..... | 700198 | 2000 Mar 06 13:27:39 | 0.4 | 6168.8 |

* Total good time with dead-time correction.

b Units are ks.
FIG. 1.—Gray-scale representations of Chandra X-ray images of NGC 4151 in the 0.3–2.5 keV band taken with various frame times. The narrow streak running northeast-southwest (P.A. 27°) across the entire field, and visible in (a) and (b), is not real but a result of the CCD readout of the intense nuclear source. (a) 0.1 s frame time. The gray scale is proportional to the square root of the X-ray intensity, ranging from 0 (white) to 100 counts pixel$^{-1}$ (black). (b) 0.4 s frame time. The gray scale is proportional to the square root of the X-ray intensity, ranging from 0 (white) to 100 counts pixel$^{-1}$ (black). (c) 3.2 s frame time. The gray scale is proportional to the square root of the X-ray intensity, ranging from 0 (white) to 71 counts pixel$^{-1}$ (black). The “hole” at the nucleus in the 3.2 s frame time image is not real but caused by pileup.

10,690 in the 0.1 and 0.4 s frame times, respectively. For both observations, the background was taken from a region between two ellipses centered on the nucleus. The large ellipse had a semimajor axis of 17.5 along P.A. 27° (the column direction of CCD readout), and the smaller ellipse had a semimajor axis of 12.5 in the direction of P.A. = 52°. This rather oddly shaped background region allowed all the background events to be extracted from the same CCD node.

The extracted spectra were grouped to a minimum of 20 and 30 counts bin$^{-1}$ in the 0.1 and 0.4 s frame time data, respectively, to allow use of $\chi^2$ statistics. The spectral resolution of ACIS-S is $\sim 0.1$ keV at 1 keV. For the bright nuclear region, the spectral resolution was not significantly degraded by this grouping. Because of the poor calibration at low energies and high background at high energies, channels below 0.3 keV and above 9 keV were ignored when modeling the spectra.

The emission from the brightest part of NGC 4151 originates in the nucleus and the unresolved emission-line regions. At least two components are needed to describe the continuum of the spectra from this region: a hard power law absorbed by an equivalent hydrogen column density of $N_H = (2-3) \times 10^{22}$ cm$^{-2}$, and a soft component that can be represented by either an absorbed power-law or a thermal bremsstrahlung model. The 0.1 s frame time spectra were...
intensity. The hole in the nucleus is not real but a result of pileup. The 179 counts pixel
NGC 4151 in the 0.3–10 keV can be described as a power law with photon index
2) plus emission lines (Table 3). The model 2 fitted with these two-component continuum models (Table 2) plus emission lines (Table 3). The model 2–9 keV flux is 4.8 × 10^{-11} \text{ ergs cm}^{-2} \text{s}^{-1}, and the photon index of the hard component \Gamma \approx 0.32. The soft X-ray spectrum below 2 keV can be described as a power law with photon index \Gamma \approx 2.6 (Table 2; Fig. 4a). An alternative description in terms of thermal bremsstrahlung gives a temperature \approx 0.57 keV (Fig. 4b). However, the emission cannot be described by solar abundance, collisionionized hot gas. The best-fit double power-law parameters agree with those obtained in a concurrent HETGS observation (Ogle et al. 2000). Previous ASCA observations (Weaver et al. 1994b) gave a 2–10 keV flux of 11–22 × 10^{-11} \text{ ergs cm}^{-2} \text{s}^{-1}, a photon index of \Gamma \approx 1.5, and an absorbing column of 2–5 × 10^{22} \text{ cm}^{-2}. The Weaver et al. (1994b) absorbing column is about the same as found in our observation and that of Ogle et al. (2000), while the photon index and flux from ASCA are significantly larger, indicating variability of the hard component. Our observations suggest that the hard component of NGC 4151 is at its lowest state since 1984 (EXOSAT observations yielded a low 2–10 keV flux of 3.6 × 10^{-11} \text{ ergs cm}^{-2} \text{s}^{-1}). The very hard power-law index found in the present observations with Chandra is unusual for a Seyfert 1 galaxy (Mushotzky 1984).

Lines were identified by adding narrow Gaussian features to the continuum model with the goal of reducing the \chi^2 value of the fit. For all cases except the combined O VII triplet, the intrinsic line width was set to zero. Both 0.1 and 0.4 s frame time data were used. Though piled up, the continuum of the 0.4 s frame time data between 0.4 and 7 keV can still be described by a double power-law model reasonably well (reduced \chi^2 = 180.8 for 179 degrees of freedom [dof]), with a rather hard photon index (\Gamma = -0.14^{+0.08}_{-0.07}) above 2 keV (Fig. 4c). This value of \Gamma is, however, too low as a result of the pileup. The low spectral resolution of the ACIS instrument does not allow us to resolve all the lines seen in the grating observation (Ogle et al. 2000), but the

![Contour plot of the 3.2 s frame time Chandra X-ray image of NGC 4151 in the 0.3–10 keV range. The 11 contour levels range from 4 to 179 counts pixel^{-1} and are proportional to the square root of the X-ray intensity. The hole in the nucleus is not real but a result of pileup.](image)

| Model\(^{a}\) | \(N_{\text{H}}\) (Soft Comp.) \((\times 10^{20}\text{cm}^{-2})\) | \(kT_0/\Gamma_1\) | \(K_1\) | \(N_{\text{H}}\) (Hard Comp.) \((\times 10^{20}\text{cm}^{-2})\) | \(\Gamma_2\) | \(K_2\) | \(\chi^2/\text{dof}\) |
|----------------|------------------|-----------------|---------|------------------|---------|---------|----------------|
| PL + PL + LINES | 29^{+0.7}_{-0.7} | 2.6^{+0.1}_{-0.1} | (7.8^{+0.4}_{-0.4}) \times 10^{-4} | 3.1^{+0.4}_{-0.4} | 0.32^{+0.05}_{-0.05} | (1.4^{+0.0}_{-0.0}) \times 10^{-3} | 66.3/65 |
| BR + PL + LINES | 20^{+0.7}_{-0.7} | 0.57^{+0.0}_{-0.0} | (2.9^{+0.0}_{-0.0}) \times 10^{-3} | 2.6^{+0.5}_{-0.5} | 0.32^{+0.10}_{-0.10} | (1.4^{+0.0}_{-0.0}) \times 10^{-3} | 70.4/69 |

\(^{a}\) Model abbreviations are “PL” for power law, “BR” for bremsstrahlung, and “LINES” for emission lines (see Table 3 for line parameters).

\(^{b}\) Units of keV.

\(^{c}\) Model normalization. For the bremsstrahlung model \(K_{\text{br}} = 3.02 \times 10^{-15} n_e n_i dV/(4\pi D^2)\), where \(n_e\) is the electron density, \(n_i\) is the ion density, and \(D\) is the distance to the source (all in cgs units). For the power-law model \(K_{\text{PL}} = \text{photons cm}^{-2} \text{s}^{-1} \text{keV}^{-1}\) at 1 keV.

### TABLE 3

**Emission Lines from the Nucleus: 0.1 s Frame Time Observations**

| Model\(^{a}\) | Energy (keV) | Line | Observed Energy (keV) | \(K\) | EW\(^{c}\) (eV) | Flux\(^{d}\) |
|----------------|-------------|------|----------------------|---------|--------------|-------------|
| I \ldots \ldots | 6.40 | Fe i Kα | 6.37^{+0.04}_{-0.04} | (1.4^{+0.0}_{-0.0}) \times 10^{-4} | 182 | 1.8 \times 10^{-4} |
| I \ldots \ldots | 0.87, 0.90, 0.91, and 0.92 | O vii RRC, Ne vii triplet | 0.91^{+0.01}_{-0.01} | (8.7^{+0.3}_{-0.3}) \times 10^{-5} | 78.0 | 7.4 \times 10^{-5} |
| I \ldots \ldots | 0.74, 0.77, and 0.82 | O vii RRC & O vii Lyβ Lyγ | 0.76^{+0.05}_{-0.05} | (4.0^{+0.0}_{-0.0}) \times 10^{-5} | 21.7 | 8.1 \times 10^{-5} |
| I \ldots \ldots | 0.561, 0.568, and 0.574 | O vii triplet | 0.58^{+0.03}_{-0.03} | (2.6^{+0.0}_{-0.0}) \times 10^{-4} | 71.0 | 4.3 \times 10^{-4} |
| II \ldots \ldots | 6.40 | Fe i Kα | 6.36^{+0.04}_{-0.04} | (1.3^{+0.0}_{-0.0}) \times 10^{-3} | 181 | 1.8 \times 10^{-4} |
| II \ldots \ldots | 0.87, 0.90, 0.91, and 0.92 | O vii RRC, Ne vii triplet | 0.91^{+0.01}_{-0.01} | (1.1^{+0.0}_{-0.0}) \times 10^{-4} | 105 | 7.4 \times 10^{-5} |
| II \ldots \ldots | 0.74, 0.77, and 0.82 | O vii RRC & O vii Lyβ Lyγ | 0.76^{+0.03}_{-0.03} | (8.7^{+0.0}_{-0.0}) \times 10^{-5} | 50.7 | 8.1 \times 10^{-5} |
| II \ldots \ldots | 0.65 | O vii Lyβ | 0.62^{+0.02}_{-0.02} | (1.6^{+0.0}_{-0.0}) \times 10^{-4} | 55.2 | 1.0 \times 10^{-4} |
| II \ldots \ldots | 0.561, 0.568, and 0.574 | O vii triplet | 0.53^{+0.07}_{-0.07} | (1.7^{+0.0}_{-0.0}) \times 10^{-4} | 37.4 | 4.3 \times 10^{-4} |

\(^{a}\) Model I: bremsstrahlung plus power law plus emission lines; model II: two power laws plus emission lines.

\(^{b}\) \(K = \text{total photons cm}^{-2} \text{s}^{-1} \text{ in the line.}\)

\(^{c}\) Equivalent width.

\(^{d}\) Total photons cm^{-2} s^{-1} in the line from HETGS observations by Ogle et al. 2000.

\(^{e}\) Modeled as a single line with width 0.05 ± 0.03 keV; this width is probably not real in view of present calibration uncertainties.
Fig. 3.—Comparison of model PSFs with observed radial profiles. In each panel, the histogram is the model PSF from the PSF library and is normalized to the 0.1 s frame time image peak, which is not piled up. The points are the observed count rates per pixel that were obtained by averaging over an annulus or segments of an annular region of radial extent 1°. Diamonds represent 0.1 s frame time data, triangles represent 0.4 s frame time data, and squares represent 3.2 s frame time data. (a) 2–9 keV band. The PSF was interpolated to 5.5 keV from the library of PSFs. The observed counts were taken from complete, circular annuli and are consistent with the PSF, so the emission in this band is unresolved. (b) 0.4–2 keV band. The PSF was interpolated to 1.2 keV. The observed counts were taken from two pie-shaped regions each with opening angle 60° along P.A. 144° and 324°, which are approximately perpendicular to the direction of elongation of the extended emission (see Fig. 1). This diagram shows that the soft emission along these directions is marginally resolved or unresolved. (c) Same energy range as (b). The counts were taken from a pie-shaped region toward the southwest (P.A. 233°) with opening angle of 120°. (d) Same as (c), but for the northeast region (P.A. 54°), with opening angle 120°.

Stronger lines are detected. The best fits to the spectra are shown in Figure 4, while the lines identified are listed in Tables 3 and 4. The errors represent the 90% confidence range for a single interesting parameter. One feature in the 0.4 s frame time spectrum, which probably results from the rapid change of effective area with energy near 2 keV, is also listed in Table 4 and labeled as “artifact.” The line fluxes from the 0.1 s frame time image agree well with those found

| Energy (keV) | Line | Observed Energy (keV) | K^a | EW^b (eV) | Flux^c |
|-------------|------|-----------------------|-----|-----------|--------|
| 6.40        | Fe I Kα | 6.43 ± 0.09 | (5.9 ± 0.3) × 10^{-5} | 92.6 | 1.8 × 10^{-4} |
| 2.25        | Artifact | ... | ... | ... | ... |
| 1.73, 1.74, 1.84, and 1.88 ... | Si I Kα, Mg xxiv Lyβ, Si xiii f, r | 1.81 ± 0.03 | (2.1 ± 0.3) × 10^{-5} | 146 | 4.0 × 10^{-5} |
| 1.33, 1.35, and 1.36 ... | Mg xii f, r, Ne x RRC | 1.38 ± 0.03 | (7.1 ± 0.3) × 10^{-6} | 257 | 2.9 × 10^{-5} |
| 1.02        | Ne x Lyα | 1.07 ± 0.02 | (2.0 ± 0.3) × 10^{-5} | 39.9 | 2.0 × 10^{-5} |
| 0.90, 0.91, and 0.92 ... | Ne xix triplet | 0.92 ± 0.01 | (6.9 ± 0.3) × 10^{-5} | 100 | 6.2 × 10^{-5} |
| 0.74, 0.77, and 0.82 ... | O vii RRC, O vii Lyβ, Lyγ | 0.81 ± 0.02 | (5.0 ± 0.3) × 10^{-5} | 54.5 | 8.1 × 10^{-5} |
| 0.65 and 0.66 ... | O vii Lyα, N vii RRC | 0.67 ± 0.05 | (8.9 ± 0.3) × 10^{-5} | 60.8 | 1.2 × 10^{-4} |
| 0.561, 0.568, and 0.574 ... | O vii triplet | 0.56 ± 0.02 | (3.5 ± 0.3) × 10^{-4} | 166 | 4.3 × 10^{-4} |

^a K = total photons cm^{-2} s^{-1} in the line.

^b Equivalent width.

^c Total photons cm^{-2} s^{-1} in the line from the HETGS observations by Ogle et al. 2000.
in the HETGS observation (Table 3). The line fluxes found from the 0.4 s frame time data tend to be lower than those obtained from the grating observation (see Table 4), probably as a result of pileup.

3.3. X-Ray Spectra of the Extended Emission

For the extended emission, we used the 3.2 s frame time observation and extracted spectra from non–piled-up regions more than 3" from the nucleus to both the northeast and southwest. The spectrum of the northeast region was extracted from a 12\arcmin7 \times 8\arcmin6 rectangle centered 7\arcmin3 northeast of the nucleus ($\alpha = 12h10m33\fs0, \delta = 39\deg24\arcmin26\farcs7$) with the longer side in P.A. 144\deg. The spectrum of the southwest region was extracted from a 12\arcmin3 \times 7\arcmin7 rectangle centered 9\arcmin2 southwest of the nucleus ($\alpha = 12h10m31\fs8, \delta = 39\deg24\arcmin17\farcs9$) with the longer side in P.A. 234\deg (Fig. 5). The total number of counts in the northeast and southwest regions are 1120 and 1776, respectively. The background region was the same as in § 3.2. The data were grouped to a minimum of 20 counts bin$^{-1}$ in each region. The spectral resolution above 1 keV was significantly reduced by this grouping, especially for the northeast region. As before,
channels below 0.3 keV and above 9 keV were ignored in spectral modeling.

The extended soft X-ray continuum emission can be modeled by a single bremsstrahlung or power-law model with photoelectric absorption (Table 5). The emission observed above 2 keV is the unresolved nuclear emission that has been spread out by the mirror PSF (see § 3.1 and Fig. 3a) and is hence modeled with an absorbed power law with photon index and absorbing column density identical to the nuclear value (§ 3.2). The absorbing column densities for the extended regions are not well constrained with the present data and were “frozen” to the Galactic value ($N_{H, \text{Gal}} = 2.19 \times 10^{20} \text{ cm}^{-2}$; Murphy et al. 1996).

It would be interesting to examine the spectral index as a function of distance from the nucleus. However, the low count rate in the extended region makes it hard to obtain such spectra. To obtain a more qualitative picture, the “hardness ratio” of the soft X-ray band (defined as the ratio of background-subtracted count rates in the 0.8–2.0 keV and 0.4–0.8 keV bands) as a function of distance from the nucleus has been obtained for the southwest region from the 3.2 s frame time observation (Fig. 6). No significant change of hardness ratio is seen between 4″ and 14″ from the nucleus.

Spectral lines were identified with the same technique as for the nucleus, and the results are shown in Table 6. He-like O and Ne triplets are seen in both the southwest and northeast regions. The 0.72–0.74 keV feature observed in both regions could be a blend of lines of H-like O and radiative recombination continuum features of O vii. The observed spectra are compared with the continuum plus emission-line models in Figure 7.

### 3.4. Comparison with Observations at Other Wavelengths

An [O iii] λ5007 contour map (Pérez-Fournon & Wilson 1990) is overlaid on the 3.2 s frame time 0.3–9 keV image in

#### FIG. 6.—Hardness ratio (defined as the ratio of the count rates in the 0.8–2 keV to the 0.4–0.8 keV band) as a function of distance from the nucleus along P.A. 233°. The hardness ratio was obtained from the 3.2 s frame time data. These data suffer from pileup at $r \leq 3$.

### TABLE 5

| Model | Region    | $N_H$ (Soft Comp.) ($\times 10^{20} \text{ cm}^{-2}$) | $kT c / T_1$ | $K_1$ | $N_H$ (Hard Comp.) ($\times 10^{21} \text{ cm}^{-2}$) | $\Gamma_2$ | $K_2$ | $\chi^2$/dof |
|-------|-----------|--------------------------------------------------|----------------|-------|--------------------------------------------------|-----------|-------|----------------|
| I     | Northeast | 2.19 (frozen) | $0.68^{\pm0.11}$ | $(5.0^{+1.9}_{-1.6}) \times 10^{-5}$ | 2.6 (frozen) | 0.32 (frozen) | $(6.2^{+1.4}_{-1.2}) \times 10^{-6}$ | 27.3/33 |
| II    | Northeast | 2.19 (frozen) | $2.5^{+0.5}_{-0.3}$ | $(1.4^{+0.2}_{-0.2}) \times 10^{-5}$ | 3.1 (frozen) | 0.32 (frozen) | $(5.5^{+0.2}_{-0.2}) \times 10^{-6}$ | 32.0/33 |
| I     | Southwest | 2.19 (frozen) | $0.41^{\pm0.04}$ | $(1.8^{+0.2}_{-0.2}) \times 10^{-4}$ | 2.6 (frozen) | 0.32 (frozen) | $(6.2^{+1.4}_{-1.2}) \times 10^{-6}$ | 43.4/48 |
| II    | Southwest | 2.19 (frozen) | $3.2^{+0.1}_{-0.2}$ | $(2.0^{+0.2}_{-0.2}) \times 10^{-5}$ | 3.1 (frozen) | 0.32 (frozen) | $(5.6^{+0.2}_{-0.2}) \times 10^{-6}$ | 54.2/48 |

* Model I: bremsstrahlung plus power law plus emission lines; model II: power law plus power law plus emission lines. (See Table 6 for emission line parameters.)
* Units of keV.
* Model normalization. For the bremsstrahlung model $K_{\text{Brem}} = 3.02 \times 10^{-15} [n_e n_i dV/(4\pi D^2)]$, where $n_e$ is the electron density, $n_i$ is the ion density, and $D$ is the distance to the source (all in cgs units). For the power-law model, $K_{\text{PL}} = \text{photons cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$ at 1 keV.

#### TABLE 6

| Model | Region    | Energy (keV) | Line       | Observed Energy (keV) | $K^b$ | EW (eV) |
|-------|-----------|-------------|------------|-----------------------|-------|---------|
| I     | Northeast | 0.90, 0.91, 0.92, and 1.02 | Ne ix triplet, Ne x Lyα | 0.96$^{+0.04}_{-0.04}$ | $(3.1^{+1.8}_{-1.5}) \times 10^{-6}$ | 160. |
| I     | Northeast | 0.74 and 0.77 | O vii RRC, O vii Lyβ | 0.72$^{+0.05}_{-0.04}$ | $(3.9^{+1.3}_{-1.0}) \times 10^{-6}$ | 101. |
| I     | Northeast | 0.561, 0.568, and 0.574 | O vii triplet | 0.58$^{+0.02}_{-0.02}$ | $(8.4^{+2.0}_{-1.9}) \times 10^{-6}$ | 127. |
| II    | Northeast | 0.90, 0.91, and 1.02 | Ne ix triplet, Ne x Lyα | 0.95$^{+0.04}_{-0.04}$ | $(4.0^{+0.2}_{-0.2}) \times 10^{-6}$ | 252. |
| II    | Northeast | 0.74 and 0.77 | O vii RRC, O vii Lyβ | 0.72$^{+0.03}_{-0.03}$ | $(5.3^{+1.5}_{-1.2}) \times 10^{-6}$ | 172. |
| II    | Northeast | 0.561, 0.568, and 0.574 | O vii triplet | 0.56$^{+0.02}_{-0.02}$ | $(1.2^{+0.2}_{-0.3}) \times 10^{-5}$ | 194. |
| I     | Southwest | 0.90, 0.91, and 1.02 | Ne ix triplet, Ne x Lyα | 0.93$^{+0.03}_{-0.03}$ | $(4.2^{+0.2}_{-0.2}) \times 10^{-6}$ | 124. |
| I     | Southwest | 0.74 and 0.77 | O vii RRC, O vii Lyβ | 0.74$^{+0.04}_{-0.04}$ | $(6.0^{+1.3}_{-1.2}) \times 10^{-6}$ | 86.6 |
| I     | Southwest | 0.561, 0.568, and 0.574 | O vii triplet | 0.58$^{+0.02}_{-0.01}$ | $(2.6^{+0.0}_{-0.2}) \times 10^{-5}$ | 178. |
| II    | Southwest | 0.90, 0.91, and 1.02 | Ne ix triplet, Ne x Lyα | 0.92$^{+0.03}_{-0.03}$ | $(5.5^{+1.0}_{-1.0}) \times 10^{-6}$ | 221. |
| II    | Southwest | 0.74 and 0.77 | O vii RRC, O vii Lyβ | 0.72$^{+0.04}_{-0.03}$ | $(8.8^{+2.2}_{-2.1}) \times 10^{-6}$ | 180. |
| II    | Southwest | 0.561, 0.568, and 0.574 | O vii triplet | 0.58$^{+0.01}_{-0.01}$ | $(3.2^{+0.2}_{-0.4}) \times 10^{-5}$ | 284. |

* Models: see Table 5.
* $K = \text{total photons cm}^{-2} \text{s}^{-1}$ in the line.
Figure 7. X-ray spectra of the extended regions of NGC 4151 extracted from the 3.2 s frame time data. The upper panels show the data points with error bars (crosses) and the model folded through the instrument response (solid line). The lower panels show the residuals to this fit. The parameters of the models are listed in Tables 5 and 6. Note that the calibration is uncertain below 0.50 keV and degrades rapidly below 0.45 keV. (a) Southwest region. The model is a bremsstrahlung plus a power law plus emission lines. (b) Southwest region. The model is two power laws plus emission lines. (c) Northeast region. The model is a bremsstrahlung plus a power law plus emission lines. (d) Northeast region. The model is two power laws plus emission lines.

Figure 8. Extended X-ray emission is well correlated with the forbidden line emission to both the northeast and southwest of the nucleus. The X-ray knot $6''$ ($\approx 380$ pc) to the southwest of the nucleus is also seen in the [O III] image, but with an $\sim 1''$ displacement.

In Figure 9, a radio contour map from MERLIN observations (Mundell et al. 1995) is overlaid on our 0.1 s frame time Chandra image. The radio jet does not align with the soft X-ray extension. The angle between the two directions is $\sim 12''$.

4. DISCUSSION

4.1. Partial Covering and Scattering

One of the early suggestions for the origin of “soft excess” is the partial covering model (Holt et al. 1980), in which the continuum from the nucleus is covered by a “clumpy” absorber. Previous studies show that a covering factor of 0.7–0.97 can account for all or a significant part of the “soft excess” (e.g., Weaver et al. 1994b). However, in the two concurrent observations presented by Ogle et al. (2000) and this paper, the photon indices for the hard and soft component were found to be $\sim 0.3$ and $\sim 2.6$, respectively. The 0.1–2 keV flux from our observation is $\sim 4 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$, which is close to the lowest value seen in the ASCA observations of $\sim 5 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ (Weaver et al. 1994b). This shows no significant variability in the soft component, in contrast to the large variability in the hard component. These results make a partial covering model unlikely. The same argument applies to the notion that the soft emission is Thomson-scattered nuclear radiation, as already noted by Ogle et al. (2000). Instead, it is most likely that the soft and hard components are intrinsically different X-ray sources.

The Thomson scattering model for the extended soft emission can be evaluated using the soft- and hard-band profiles (Fig. 3). The hard-band profile is consistent with the mirror PSF, indicating that there is no detectable intrinsically extended hard emission. This allows an upper limit to the fractional brightness of any hard nuclear emission that is Thomson scattered by the extended gas to be obtained. Because Thomson scattering is wavelength independent, this upper limit can be compared with the brightness of the extended, soft emission, expressed as a fraction of the soft nuclear emission. Using the 0.1 s frame time observations in Figure 3a, the 2–9 keV brightness within 1$''$ of the nucleus is 0.12 counts pixel$^{-1}$ s$^{-1}$, and the intrinsic 2–9 keV bright-
ness between 4" and 5" from the nucleus is less than $3.9 \times 10^{-5}$ counts pixel$^{-1}$ s$^{-1}$, which represents an upper limit to the Thomson-scattered hard radiation. The corresponding numbers for the 0.4–2 keV emission are 0.13 counts pixel$^{-1}$ s$^{-1}$ for the nucleus and 2.6 $\times 10^{-4}$ counts pixel$^{-1}$ s$^{-1}$ between 4" and 5" from the nucleus in the southwest region (Fig. 3c). Defining $R \equiv$ (brightness between 4" and 5" from the nucleus)/(brightness within 1" of the nucleus), we have $R_{2.9\text{keV}} < 3.2 \times 10^{-4}$ and $R_{0.4-2\text{keV}} = 2 \times 10^{-3}$. The argument indicates that the extended soft emission is not Thomson-scattered nuclear radiation as long as the intensity of the nuclear radiation radiated toward the putative scattering region is equal to that radiated toward Earth. The nuclear 2–9 keV radiation radiated toward the extended region may be stronger than that radiated in our direction because the latter is absorbed. Such an effect decreases $R_{2-9\text{keV}}$ and increases the discrepancy between $R_{2-9\text{keV}}$ and $R_{0.4-2\text{keV}}$. If the soft nuclear emission is absorbed by more than the low column we obtained by fitting the spectrum, it is possible that more soft radiation is radiated from the nucleus toward the extended emission than toward us. This effect would reduce $R_{0.4-2\text{keV}}$ and could potentially remove the discrepancy between $R_{0.4-2\text{keV}}$ and $R_{2-9\text{keV}}$. While such cannot be ruled out, we consider it unlikely that the extended X-ray emission is Thomson-scattered nuclear radiation.

4.2. A Two-Phase Model for the Extended X-Ray Emission

The close association between the extended soft X-ray emission and the optical line emission in NGC 4151 suggests that the X-rays may arise from hot gas in pressure equilibrium with the extended narrow-line region (ENLR) (Heckman & Balick 1983; Morse et al. 1995). Gas of $10^6-10^8$ K is needed to confine the cooler gas clouds (Krolik, McKee, & Tarter 1981, hereafter KMT81; Krolik & Vrtilek 1984). Grating observations with the Chandra HETGS show clear signatures of both photoionization and collisional ionization in the X-ray–emitting gas in the NLR. This indicates that at least two phases exist in the plasma, one being hot ($T \simeq 10^7$ K) and collisionally ionized and the other warm ($T \gtrsim 10^6$ K) and photoionized (Ogle et al. 2000).

Penston et al. (1990) derived emissivity-weighted estimates for the electron density and electron temperature in the southwest optical ENLR of $n_e \simeq 220$ cm$^{-3}$ and $T_e \simeq 14,130$ K, corresponding to a pressure of $n_e T_e \simeq 3.1 \times 10^6$ cm$^{-3}$ K. If the warm and hot clouds are in a rough pressure equilibrium, the density of the hot phase gas at a temperature of $T_e = 4.8 \times 10^6$ K (the bremsstrahlung temperature in the southwest regions) should be $n_e \simeq 0.6$ cm$^{-3}$. Assuming that the hot gas in the observed southwest region uniformly fills a cylinder with a radius of 246 pc ($\simeq 3.85$) and a height of 787 pc ($\simeq 12.3$), the number density inferred from the bremsstrahlung description of the continuum of the southwest radiation (see Table 5) is found to be $n_e \simeq 0.5$ cm$^{-3}$. This is close to that needed for pressure balance. Using the two–power-law spectrum obtained from the 0.1 s frame time observation (§ 3.2) and adopting a spectral turnover near 100 keV (Maisack et al. 1993), we obtain a photoionizing luminosity $L_{1.3 \text{keV} - 100\text{keV}} = 6.2 \times 10^{43}$ ergs cm$^{-3}$ s$^{-1}$. The ionization parameter (defined as $\xi \equiv L/4\pi\epsilon$, where $\epsilon$ is the temperature of the bremsstrahlung model) is much lower than the Compton temperature ($T \gtrsim 10^8$ K; see KMT81). Given our low spectral resolution, we cannot tell whether the emission lines we see from the extended region are collisionally ionized or photoionized. Ogle et al. (2000) identified photoionized N VII, O VII, O VIII, Ne IX, and Ne X in the nuclear region from the narrowness of their radiative recombination con-
We see lines (some tentatively) of O VII, O VIII, Ne IX, and Ne X from the extended regions (Table 6). If these species are created by photoionization, the ionizing parameter lies in the range $1.6 < \log \xi < 2.2$, where $\xi \equiv L/nr^2$ (Kallman & McCray 1982). Using the ionization luminosity given above and a typical radius of 500 pc, these values of $\xi$ imply $0.2 < n < 0.7$ cm$^{-3}$. The temperature of this gas would be $\approx 10^{4.5}$ K according to Kallman & McCray (1982). Higher spectral resolution observations are needed to determine whether these lines are photoionized in such a warm gas or collisionally ionized in a hotter one.

5. CONCLUSIONS

We have obtained high-sensitivity X-ray imaging spectroscopy of NGC 4151 with the *Chandra* X-Ray Observatory. The soft X-ray emission (below 2 keV) is spatially resolved and extends as far as $\approx 900$ pc to the southwest and $\approx 700$ pc to the northeast of the nucleus. There is a close correlation between the extended soft X-ray and [O III] $\lambda$5007 emissions on the hundreds of parsec scale. The 0.4–9 keV spectra of the nucleus and the extended regions to the southwest and northeast of the nucleus have been obtained. The X-ray emission above 2 keV is spatially unresolved and is well described by an absorbed power law. The spectrum above 2 keV is harder and the flux lower than in observations made with *ASCA* in 1993 (Weaver et al. 1994b). The spectrum below 2 keV, on the other hand, is softer than found previously. The large difference between the soft and hard spectral shapes does not favor the partial covering or scattering model of the “soft excess.” Instead, it is likely that the hard and soft nuclear components represent intrinsically different X-ray sources. We have shown that a model in which the extended emission is electron-scattered nuclear radiation is extremely implausible. With the temperature ($\approx 4.8 \times 10^7$ K) inferred from a bremsstrahlung interpretation of the X-ray spectrum, this hot gas is close to pressure equilibrium with the gas that radiates the optical line emission. While the extended emission is certainly thermal, our observations do not permit a clear distinction between a photoionized and collisionally ionized gas. It is likely that both components are present, given the findings of Ogle et al. (2000) for the nuclear region.

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APPENDIX

AN OFF-NUCLEAR X-RAY SOURCE

An unresolved X-ray source [α(2000.0) = 12h10m22s37, δ(2000.0) = 39°23′17″] $\approx 2\farcs2$ southwest of the nucleus (P.A. $\approx 241°$) of NGC 4151 has been detected in the 3.2 s frame time observation. The total counts within a 3″ radius centered on the point source are 249. We obtained a spectrum of the source (Fig. 10). The spectrum can be well described by a power law absorbed by the Galactic column density $N_{\text{H, Gal}} \approx 2.19 \times 10^{20}$ cm$^{-2}$; Murphy et al. 1996), with $\chi^2 = 27.2$ for 25 dof. The best-fit photon index $\Gamma = 1.7^{+0.1}_{-0.2}$, and the model flux for the 0.3–5 keV energy range is $6.8 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$, corresponding to a luminosity of $1.4 \times 10^{39}$ ergs s$^{-1}$, if the source is associated with NGC 4151. This source lies approximately along the extension of the southwest extended emission to larger radii. There is a weak optical object nearby at the limit of the Digitized Sky Survey with an estimated POSS-E magnitude of $\approx 20$. It is unclear whether this X-ray source is physically associated with NGC 4151. Similar coincidences have been seen in Mrk 3, Pictor A, and NGC 4258, each of which has a faint, compact X-ray source close to the extension of the radio jets (Morse et al. 1995; Wilson, Young, & Shopbell 2001b; Wilson, Yang, & Cecil 2001a).

![Fig. 10](image-url). X-ray spectrum of the off-nuclear source described in the Appendix. The spectrum is extracted from the 3.2 s frame time observation. The upper panel shows the data points with error bars (crosses) and the model folded through the instrument response (solid line). The lower panel shows the $\chi^2$ residuals to this fit. The model is an absorbed power law.
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