A *CHANDRA* X-RAY STUDY OF NGC 1068. I. OBSERVATIONS OF EXTENDED EMISSION

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ABSTRACT

We report subarcsecond-resolution X-ray imaging spectroscopy of the archetypal type 2 Seyfert galaxy NGC 1068 with the *Chandra* X-Ray Observatory. The observations reveal the detailed structure and spectra of the 13 kpc extent nebulosity previously imaged at lower resolution with *ROSAT*. The *Chandra* image shows a bright, compact source coincident with the brightest radio and optical emission; this source is extended by $\approx 1''.5$ (165 pc) in the same direction as the nuclear optical line and radio continuum emission. Bright X-ray emission extends $\approx 5''$ (550 pc) to the northeast and coincides with the northeast radio lobe and gas in the narrow-line region. The large-scale emission shows trailing spiral arms and other structures. Numerous point sources associated with NGC 1068 are seen. There is a very strong correlation between the X-ray emission and the high-excitation ionized gas seen in *Hubble Space Telescope* and ground-based [O III] $\lambda 5007$ images. The X-rays to the northeast of the nucleus are absorbed by only the Galactic column density and thus originate from the near side of the disk of NGC 1068. In contrast, the X-rays to the southwest are more highly absorbed and must come from gas in the disk or on the far side of it. This geometry is similar to that inferred for the narrow-line region and radio lobes. Spectra have been obtained for the nucleus, the bright region $\approx 4''$ to the northeast, and eight areas in the extended emission. The spectra are inconsistent with hot plasma models, the best approximations requiring implausibly low abundances ($\lesssim 0.1 Z_{\odot}$). Models involving two smooth continua (either a bremsstrahlung plus a power law or two bremsstrahlungs) plus emission lines provide excellent descriptions of the spectra. The emission lines cannot be uniquely identified with the present spectral resolution (~ 110 – 190 eV), but are consistent with the brighter lines seen in the *XMM-Newton* reflection grating spectrometer (RGS) spectrum below 2 keV. Hard X-ray (above 2 keV) emission, including an iron line, is seen extending $\approx 20''$ (2.2 kpc) northeast and southwest of the nucleus. Lower surface brightness, hard X-ray emission, with a tentatively detected iron line, extends $50''$ (5.5 kpc) to the west and south. Our results, when taken together with the *XMM-Newton* RGS spectrum, suggest photoionization and fluorescence of gas by radiation from the Seyfert nucleus to several kpc from it. The facts that (1) the large-scale (arcminute) and small-scale (few arcseconds) X-ray emissions align well and (2) the morphology of the large-scale emission does not correlate well with the starburst suggests that the starburst is not the dominant source of the extended X-rays.

Subject headings: galaxies: active — galaxies: individual (NGC 1068) — galaxies: nuclei — galaxies: Seyfert — X-rays: galaxies

1. INTRODUCTION

Extended X-ray emission in Seyfert galaxies represents a potentially powerful probe of these active galactic nuclei. Such X-rays could originate from either a hot, collisionally ionized or a much cooler photoionized gas. Both may plausibly be expected to be present in these objects. The narrow-line regions of Seyfert galaxies are known to be the sites of mass motions of several hundreds to ~ 1000 km s^{−1}. Shocks associated with these motions will generate gas with temperatures $\approx 10^6$ – 10^7 K. Hot gas may also be present in the form of outflowing winds driven by radiation or radio jets from the nucleus. The compact, hard, UV–soft X-ray nuclear continuum source is believed to photoionize the narrow-line region. Lines from highly ionized species, such as He II, [Ne V], [Fe VII], [Fe X], [Fe XI], and [Fe XIV], are found in the optical and infrared spectra of these objects. X-ray lines from highly ionized species may therefore also be expected. High-velocity shocks can also be powerful

sources of ionizing radiation and, if present, should provide both collisionally and photoionized gas. By searching for both of these components, X-ray observations can probe whether shocks are significant sources of ionizing radiation for the narrow-line region. Extended X-ray emission can also arise through electron scattering and fluorescence of the nuclear radiation in extended gas. Morphological correspondences between the X-ray-emitting gas and the optical line and radio continuum structures may provide clues to the nature of the X-ray emission.

For these reasons, we have begun a program of observing Seyfert galaxies with *Chandra*. Previous X-ray observatories have lacked the high spatial resolution ($\lesssim 1''$), wide energy coverage (0.1–10 keV), and good spectral resolution (~ 130 eV from the CCD detectors) of *Chandra*. These capabilities are ideal for investigation of extended gas in Seyfert galaxies, and in this paper we present the results of observations of the nearby Seyfert 2 galaxy NGC 1068.

NGC 1068 was observed on three occasions with the *Einstein* observatory IPC by Monier & Halpern (1987). They found that the 0.1–4.5 keV spectrum could be

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described by a power law with energy index $\alpha = 2.0 \pm 0.3$ and absorbing column density consistent with the Galactic value. Combination of *EXOSAT* and *Einstein* IPC observations (Elvis & Lawrence 1988) showed that the X-ray spectrum can be decomposed into two components: a steep low-energy (< 2 keV) part with $\alpha = 3.5$, and a flat high-energy (2–10 keV) part with $\alpha \simeq 0.7$. This was the first detection in a Seyfert 2 galaxy of the hard power-law X-ray source known to be present in Seyfert 1 galaxies. Any intrinsic absorption was shown to be small ($N_{\text{H}} < 3 \times 10^{20}$ atoms cm^{-2}). *Ginga* observations (Koyama et al. 1989) confirmed the presence of the hard source above 2 keV, and also discovered an intense iron line with equivalent width 1.3 ± 0.1 keV, in accord with the predictions of Krolik & Kallman (1987). Marshall et al. (1993) obtained a higher spectral resolution (FWHM $\simeq 100$ eV) observation with the Broad Band X-Ray Telescope (BBXRT). They found a total equivalent width for the Fe K line of 2.8 keV, and modeled the line profile in terms of three components corresponding to fluorescence of neutral (and lowly ionized) iron and recombination into both He-like and H-like iron. Fe L-shell emission was also detected. In a study with *ASCA*, Ueno et al. (1994) found emission from the H-like and/or He-like ions of Ne, Mg, Si, and S and confirmed the Fe L and Fe K features found by Marshall et al. (1993). The best-fit power-law spectrum above 3 keV has energy index $\alpha \simeq 0.3 \pm 0.3$. Ueno et al. (1994) interpreted the steep low-energy (< 3 keV) spectrum in terms of a two-temperature (0.59 and 0.14 keV), optically thin coronal plasma model. Iwasawa, Fabian, & Matt (1997) reanalyzed the *ASCA* data, confirming the three components to the Fe K line complex, which they interpreted with a model of cold and warm reflection. Netzer & Turner (1997) developed both photoionization and hot plasma models, including a hard reflected continuum. Their photoionized gas model is in good agreement with the emission lines observed by *ASCA* assuming solar metallicity for all elements except iron, which is more than twice solar, and oxygen, which is less than 0.25 solar. NGC 1068 has recently been studied with *BeppoSAX*. Matt et al. (1997) detected the galaxy in the 20–100 keV band, supporting models envisaging a mixture of both neutral and ionized reflections of an otherwise invisible nuclear source. The nucleus is completely obscured at all energies, implying it is “Compton-thick”—i.e., the column density of absorbing matter exceeds $N_{\text{H}} \sim 10^{25}$ atoms cm^{-2} (see also Matt et al. 2000). Soft X-ray spectroscopy with *BeppoSAX* (Guainazzi et al. 1999) reveals a spectrum rich in $K\alpha$ transitions of various elements below 3 keV.

The only X-ray image of NGC 1068 was obtained with the *ROSAT* HRI by Wilson et al. (1992) with $4''$ – $5''$ resolution. The observed X-ray emission could be divided into three components: (1) an unresolved (radius $\leq 3''$) source associated with the Seyfert nucleus; (2) resolved circumnuclear (radius $< 15''$) emission extending preferentially toward the northeast; and (3) large-scale ($15'' < \text{radius} < 60''$) emission aligned northeast-southwest. Wilson et al. (1992) interpreted the circumnuclear emission as thermal emission from a nuclear wind and the large-scale emission as either associated with the disk starburst or an extension of the nuclear wind to larger radii. Further *ROSAT* HRI observations were reported by Wilson & Elvis (1997).

Very recently, Paerels et al. (2000) have reported a high spectral resolution observation of NGC 1068 with the

XMM-Newton Reflection Grating Spectrometer (RGS). Their spectrum reveals a large number of emission lines below 2 keV. Based on the narrowness of the recombination radiation continua, the fact that the forbidden lines are stronger than the resonance lines in helium-like triplets, and the weakness of Fe L emission compared to Fe K emission, Paerels et al. (2000) conclude that the emission is dominated by recombination in cool X-ray photoionized gas. The N and O helium-like triplets may contain a $\lesssim 30\%$ component in collisional equilibrium.

The present paper is organized as follows. In § 2 we describe the observations and their reductions. Section 3 provides a brief discussion of the X-ray morphology, while § 4 presents the X-ray spectra obtained for the nucleus and five spatially extended regions. A comparison of the X-ray images with those in other wavebands is presented in § 5, and conclusions are given in § 6. Future papers will address the compact sources in the field and present a more detailed analysis of the extended emission.

NGC 1068 is at a heliocentric redshift of $z = 0.00379$ (de Vaucouleurs et al. 1991), which, after correction to the frame of the microwave background and assuming $H_0 = 50$ $\text{km s}^{-1} \text{Mpc}^{-1}$ and $q_0 = 0$, corresponds to 22.8 Mpc, so $1''$ is equivalent to 110 pc. The Galactic column density toward NGC 1068 is $N_{\text{H}}(\text{Gal}) = 2.99 \times 10^{20} \text{ cm}^{-2}$ (Murphy et al. 1996).

2. OBSERVATIONS AND REDUCTION

Since the nucleus of NGC 1068 is known to be a strong X-ray source, we were concerned that “pile-up” could affect the *Chandra* observations. In order to measure the *Chandra* count rate from the nucleus and circumnuclear regions, we first obtained a short observation (observation ID 343) of NGC 1068 on 1999 December 9 using chip S3 (backside illuminated) of the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2000). Single exposures with a 0.1 s frame time were alternated with two exposures with a 0.4 s frame time, the total integration time being $\lesssim 1$ ks. This observation showed that the nucleus is significantly piled up in the 0.4 s frame time, but not in the 0.1 s frame time. It also demonstrated that the count rate in the region extending $\simeq 6''$ northeast from the nucleus is so high that data obtained from this region with the default frame time of 3.2 s would be piled up, but data obtained with a 0.4 s frame time would not be piled up. On this basis we decided to observe NGC 1068 for separate, longer exposures in all of the 0.1, 0.4, and 3.2 s frame times. The longer 0.1, 0.4, and 3.2 s frame-time observations were thus designed to study primarily the X-ray emission of the nucleus, the extended region to the northeast of the nucleus, and the larger scale emission, respectively.

These longer integrations were taken with the ACIS instrument in two separate observations. On 2000 February 21 the standard 3.2 s frame time was used. CCDs I2, I3, S1, S2, S3, and S4 were read out, although all the detected X-ray emission from NGC 1068 is on S3. On 2000 February 22 the readouts were alternated between one 0.1 s and two 0.4 s frame times in order to mitigate the effects of pile-up in the inner regions, as discussed above. The data were screened for times of high background count rates and aspect errors in the usual way. The 3.2, 0.4, and 0.1 s frame-time data have total good exposure times of 47016.2, 11465.4, and 1433.2 s, respectively. The “live times” for the alternating mode exposures were given incorrectly in the

FIG. 1.—Extraction regions of the larger scale emission superposed on a gray-scale image derived from the 3.2 s frame-time data. Excluded point sources are indicated by circles.

header and had to be computed separately. A corrected formula for the exposure time (G. Allen 2000, private communication) was used, and the resulting live times are equal to the frame time multiplied by the number of exposures taken with that frame time.

Spectra and instrument responses were generated using CIAO Version 1.1.5 and analyzed with XSPEC Version 11.0.1. Spectra were grouped to have at least 25 counts per energy bin to ensure that the χ^2 fitting of the data was valid. When extracting spectra from complex regions, the BACKSCAL keyword (equal to the fractional area of the chip occupied by the extraction region) was computed by hand, since the values generated by CIAO are often incorrect.

In the absence of the gratings, X-ray spectra from CCD detectors such as ACIS are not invertible, i.e., one cannot uniquely determine the X-ray spectrum from the observed counts. To model such data the following technique is used. A parameterized model of the source spectrum is computed and folded through the instrument response. The folded model and data are then compared using, e.g., the χ^2 test. Parameters of the model spectrum are adjusted to minimize the χ^2 difference between the folded model and the data. The error bars for a single parameter are given by the range over which that parameter can be varied with $\Delta\chi^2 = 2.706$, keeping the other model parameters fixed. This is equivalent to the 90% confidence interval for a single interesting parameter.

The backside-illuminated S3 chip has a high sensitivity to very soft X-rays, and significant counts at ~ 0.1 keV were seen from all regions. However, the instrument response is uncertain below 0.50 keV, and this uncertainty increases toward lower energies. We thus restricted our modeling to photon energies above 0.25 keV.

2.1. Nucleus

Counts were extracted from a $3''.75$ diameter circle centered on the nucleus. The 3.2 s frame-time data are extremely piled up and cannot be used for spectral fitting. In the 0.4 s frame-time data there are 25251 counts, corre-

sponding to a count rate of 2.20 ± 0.014 counts s^{-1} . In the 0.1 s frame-time data there are 4760 counts, corresponding to a count rate of 3.32 ± 0.048 counts s^{-1} . The difference in count rate is due, in part, to the presence of pile-up in the 0.4 s frame-time data. The background is negligible in both this and the northeast region.

2.2. Northeast Region

Counts were extracted from a $4''.1 \times 4''.6$ rectangle with longer length in position angle, P.A. = 45° , centered on the extended emission $4''.25$ to the northeast of the nucleus. This region does not overlap with the region used to extract the spectrum of the nucleus. In the 3.2 s frame-time data there are 26871 counts, corresponding to a count rate of 0.57 ± 0.003 counts s^{-1} . In the 0.4 s frame-time data there are 10069 counts, corresponding to a count rate of 0.88 ± 0.01 counts s^{-1} . In the 0.1 s data there are 1349 counts, corresponding to a count rate of 0.94 ± 0.03 counts s^{-1} . Thus, there is significant pile-up in the 3.2 s frame-time data in this region.

2.3. Larger Scale Emission

The distribution and spectrum of larger scale emission was investigated with the 3.2 s frame-time data. The large-scale region was divided into four quadrants with position angles $250^\circ \rightarrow 340^\circ$ (quadrant A), $340^\circ \rightarrow 70^\circ$ (quadrant B), $70^\circ \rightarrow 160^\circ$ (quadrant C), and $160^\circ \rightarrow 250^\circ$ (quadrant D). Position angle $\sim 25^\circ$, the bisector of quadrant B, corresponds to the approximate position angles of the radio emission and narrow-line regions to the northeast of the nucleus. Extraction regions between nuclear distances of $5''$ and $60''$ within quadrants A, B, C, and D are termed the “west,” “north,” “east,” and “south” regions, respectively, and are shown in Figure 1. Obvious point sources determined by eye were excluded. Pile-up is not significant in any of these regions.

It is difficult to determine the spectrum of the background for the larger scale emission, since there are no source-free regions nearby. To overcome this problem, we used a compilation of observations of relatively blank fields, from which discrete sources have been excised. For a particular source-extraction region, a corresponding background region is taken from this compilation. The two regions have the same physical location on the S3 chip. The background images and software² of Maxim Markevitch were used for this procedure.

3. X-RAY MORPHOLOGY

Gray-scale images of the 0.1 and 0.4 s frame-time *Chandra* X-ray observations of NGC 1068 are shown in Figures 2 and 3, respectively. The brightest region, which we refer to as the nucleus, extends $\approx 1''.5$ to the northeast. Somewhat fainter X-ray emission extends $\approx 6''.5$ northeast of the nucleus in P.A. $\sim 35^\circ$ – 40° , and perpendicular to this direction from $2''.5$ southeast to $2''.5$ northwest of the nucleus. There is a second peak of emission $3''.5$ to the northeast of the nucleus, with a brightness equal to approximately 15% of the nucleus; this peak lies within the “northeast region” (see § 2.2).

A gray-scale image of the 3.2 s frame-time observation is shown in Figure 4. This image agrees well with the *ROSAT*

² Available at: <http://hea-www.harvard.edu/~maxim/axaf/acisbg/>.

FIG. 2.—Gray-scale representation of the *Chandra* X-ray image of NGC 1068 in the 0.25–7.50 keV band taken with a 0.1 s frame time. Here and in subsequent figures, coordinates are for epoch J2000.0.

HRI image (Wilson et al. 1992) when allowance is made for the lower resolution ($4''$ – $5''$) of the latter. Two bright “prongs” of X-ray emission extend from the bright region around the nucleus. One extends from the northern tip along P.A. 330° for $7''.5$, and the second extends from the southern tip along P.A. 90° for $6''.5$ before turning to follow P.A. 5° for $4''$. Significant extended X-ray emission is seen out to at least $60''$ to the northeast, $50''$ to the southwest, $20''$ to the northwest, and $30''$ to the southeast of the nucleus. The most obvious large-scale structures appear to be “spiral arms” that curve to lower P.A. with increasing radius from the nucleus, i.e., they are “trailing” arms. They can also be seen in an image of the 3.2 s frame-time data that has been smoothed by a Gaussian of $\sigma = 0''.5$ (Fig. 5).

FIG. 3.—Gray-scale representation of the *Chandra* X-ray image of NGC 1068 in the 0.25–7.50 keV band taken with a 0.4 s frame time.

FIG. 4.—Gray-scale representation of the *Chandra* X-ray image of NGC 1068 in the 0.25–7.50 keV band taken with a 3.2 s frame time. The linear feature running from P.A. 78° across the nucleus to P.A. 258° is an instrumental effect.

The images also show many point sources of X-ray emission associated with NGC 1068.

The X-ray morphologies in the 0.25–0.80, 0.80–2.00, and 2.00–7.50 keV bands are shown in Figure 6 for the 0.1, 0.4, and 3.2 s frame-time observations. The 0.25–0.80 keV X-ray emission has the greatest spatial extent, covering the range described above. The nucleus, the northeast region, the two “prongs,” and the trailing arms are clearly seen. Only a few point sources, however, appear in these soft X-ray images. In the 0.80–2.00 keV energy band, there is still significant emission out to tens of arcseconds, and many more point

FIG. 5.—Gray-scale representation of the *Chandra* X-ray image of NGC 1068, taken with a 3.2 s frame time and smoothed by a Gaussian of $\sigma = 0''.5$. The linear feature running from P.A. 78° across the nucleus to P.A. 258° is an instrumental effect.

FIG. 6.—Gray-scale representations of *Chandra* X-ray images of NGC 1068 in three energy bands and for each of the frame times used. The top row has a 3.2 s frame time, the center row a 0.4 s frame time, and the bottom row a 0.1 s frame time. In the left column the energy range is 0.25–0.80 keV, the center column 0.80–2.00 keV, and the right column 2.00–7.50 keV.

sources are visible. In the hardest energy band, 2.00–7.50 keV, emission extends at least $\sim 13''$ to the northeast and southwest of the nucleus and at least $\sim 4''$ to the northwest and southeast. The two “prongs” (to the north and east) do not stand out in hard X-rays, perhaps because of the lower sensitivity in this band. Since the point-spread function (PSF) at the location of the nucleus is circularly symmetric, the observed elongated, extended hard X-rays are real. In addition, many hard point sources are clearly seen $\sim 20''$ from the nucleus.

4. X-RAY SPECTRA

4.1. Nucleus

4.1.1. Thermal Plasmas

Initially, the X-ray spectrum of the nucleus was modeled as an absorbed hot plasma with solar metal abundances. We used the “MEKAL” model (Mewe et al. 1985, 1986; Kaastra 1992; Liedahl, Osterheld, & Goldstein 1995; Arnaud & Rothenflug 1985; Arnaud & Raymond 1992), which is included in the X-ray spectral fitting software XSPEC. The 0.1 s frame-time data were used, since these do not suffer from pile-up. The model does not fit the data (see Table 1), so a single hot plasma can be ruled out. Such plasmas overproduce Fe L emission lines (i.e., transitions to

the $n = 2$ level) between 0.7 and 1.2 keV, and underproduce the high-energy continuum above a few keV. A better fit is obtained if the metal abundances are allowed to vary, but the best-fit value of zero is implausible for the nucleus of a spiral galaxy.

A model consisting of two hot plasmas, with temperatures of 0.17 and 0.73 keV and metal abundances of 3.0% and 2.7% of solar, respectively, provides an adequate description of the spectrum below 2 keV ($\chi^2 = 139$ for 74 degrees of freedom [dof]). Again, such low metal abundances are unlikely to be found in the inner regions of a spiral galaxy, so multiple hot plasma models are implausible for the nucleus of NGC 1068.

4.1.2. Bremsstrahlung Plus Power-Law Plus Emission Lines

Many lines are seen below 1 keV in the *XMM-Newton* RGS spectrum (Paerels et al. 2000), but these are confused by the limited spectral resolution of the *Chandra* ACIS spectrum reported here. Individual lines are sufficiently narrow to be unresolved by ACIS. We therefore decided to take a more phenomenological approach, modeling the data by a continuum plus individual emission lines. First, the continuum was described by a smooth model consisting of a bremsstrahlung plus a power law, both absorbed by the Galactic column. The residuals between the data and this

TABLE 1
SPECTRAL FITS TO THE NUCLEUS FROM 0.1 s FRAME-TIME OBSERVATION

Model ^a	N_H ($\times 10^{20} \text{ cm}^{-2}$)	Temperature (keV)	Abundance ($\times Z_\odot$)	Photon Index	Normalization ^b	χ^2/dof
MEKAL	2.99 ^c	0.65	1.0 ^c		$K_{\text{MEKAL}} = 1.6 \times 10^{-3}$	2415/88
Brem.....	2.99 ^c	0.53			$K_{\text{Brem}} = 1.1 \times 10^{-2}$	321/88
Brem + PL	2.99 ^c	0.46		0.83	$K_{\text{Brem}} = 1.2 \times 10^{-2}$ $K_{\text{PL}} = 2.0 \times 10^{-4}$	202/86
Brem + PL + lines.....	2.99 ^c	$0.45^{+0.03}_{-0.08}$		$1.01^{+0.86}_{-1.15}$	$K_{\text{Brem}} = 1.0^{+0.1}_{-0.1} \times 10^{-2}$ $K_{\text{PL}} = 2.3^{+3.4}_{-1.9} \times 10^{-4}$	67/64

^a Model abbreviations: MEKAL: Mewe, Kaastra, & Liedahl thermal plasma; PL: power law; Brem: bremsstrahlung.

^b The model normalization are $K_{\text{MEKAL}} = 10^{-14} \int n_e n_H dV / [4\pi(1+z)D_A^2]$, $K_{\text{Brem}} = 3.02 \times 10^{-15} \int n_e n_t dV / (4\pi D^2)$, and $K_{\text{PL}} = \text{photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$ at 1 keV; n_e is the electron density (cm^{-3}), n_H is the hydrogen density (cm^{-3}), n_t is the ion density (cm^{-3}), D is the distance to the source (cm), and D_A is the angular size distance to the source (cm).

^c Fixed parameter.

smooth model were inspected by eye. Emission lines were then added to the model at energies expected to reduce the value of χ^2 . The energy and flux of these lines were free parameters. This process was repeated, adding lines until either an acceptable fit was achieved, or no further improvement was possible. Finally, our observed line energies were compared with those of the *XMM-Newton* RGS spectrum (a hard copy of which was kindly provided by F. Paerels) and, if agreement found, identified with lines therein.

The 0.1 s frame-time data are well described by a 0.45 keV bremsstrahlung plasma plus a hard power law of photon index $\Gamma = 1.01^{+0.86}_{-1.15}$ plus a number of narrow emission lines, all absorbed by the Galactic column (last model in Table 1). The spectrum and best-fitting model are shown in Figure 7, and the emission lines are listed in Table 2. Radiative recombination continua (RRC) are due to free-bound transitions from energy levels just above the ionization threshold; hence, these lines start at the ionization threshold energy, and extend to higher energies (e.g., Paerels et al. 2000).

Our spectrum below 2 keV is generally consistent with lines seen in the *XMM-Newton* RGS spectrum (Paerels et al. 2000). The lines near and above 2 keV cannot be uniquely identified but are well described by neutral,

hydrogen-like, or helium-like lines of Si, S, or Ar, with the exception of lines between 6.40 and 6.97 keV attributed to Fe. The Fe line complex is well described by a neutral Fe line with an equivalent width of 2.24 keV, although it should be noted that the true level of the continuum at the iron-line energy is difficult to determine. The iron line is better resolved in the 0.4 s frame-time data (see below). In view of the low signal-to-noise ratio, the line flux densities are quite uncertain.

The best-fitting model has an unabsorbed 0.5–2.0 keV flux of $5.8 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$, corresponding to an unabsorbed rest-frame 0.5–2.0 keV luminosity of $3.6 \times 10^{41} \text{ ergs s}^{-1}$ and an unabsorbed 2.0–10.0 keV flux of $3.8 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$, corresponding to an unabsorbed rest-frame 2.0–10.0 keV luminosity of $2.3 \times 10^{41} \text{ ergs s}^{-1}$. The 2.0–10.0 keV flux and luminosity will have fractional errors comparable to the power-law component of the model, listed in Table 1.

The 0.4 s frame-time observation of the nucleus suffer from pile-up, and it is difficult to determine the true shape of the continuum and the individual line fluxes. A recent model by Davis (2001), which is included as part of the Interactive Spectral Interpretation System (ISIS),³ includes effects of pile-up in modeling spectra. We fitted the same spectral model to the 0.4 s frame-time data as was used to describe the 0.1 s frame-time data, with the continuum parameters allowed to vary and the emission-line parameters fixed. The residuals between the data and this model were examined by eye and any clear discrepancies noted. The fluxes of model lines at energies near such discrepancies were then allowed to vary in an attempt to improve the fit. If this did not provide a satisfactory improvement, the line energy was also allowed to vary. If no model line existed near an obvious feature, a new line was added. The reduced χ^2 values for these overall fits were not as good as those for the 0.1 s frame-time data because we kept most of the line parameters fixed, even though very small changes may have improved the agreement between data and model. The pile-up fraction was estimated to be 22%, and the continuum parameters were close to those found for the 0.1 s frame-time data; the bremsstrahlung component was 0.1 keV warmer, and the power-law component was slightly harder (but within the 0.1 s frame-time error bars) than the parameters derived from the 0.1 s frame-time observations. These small discrepancies are probably a result of imperfect modeling of the pile-up.

FIG. 7.—X-ray spectrum of the nucleus (defined in § 2.1) of NGC 1068 extracted from the 0.1 s frame-time data. The top panel shows the data points with error bars (*crosses*), with the model folded through the instrument response (*uppermost solid line passing through the data points*). The individual components of the model are plotted below this. The bottom panel shows the χ residuals from this fit. The parameters of the model are listed in Tables 1 and 2. Note that the calibration is uncertain below 0.50 keV and degrades rapidly below 0.45 keV.

³ Available at: <http://space.mit.edu/ASC/ISIS>.

TABLE 2
X-RAY SPECTRAL LINES FROM THE NUCLEUS

Frame Time (s)	Energy (keV)	Line	Observed Energy (keV)	K^a
0.1.....	0.37	C vi Ly α	$0.34^{+0.02}_{-0.01}$	$3.4^{+1.6}_{-1.9} \times 10^{-4}$
0.1.....	0.43	N vi triplet	$0.42^{+0.01}_{-0.01}$	$5.1^{+1.7}_{-1.9} \times 10^{-4}$
0.1.....	0.56–0.57	O vii triplet	$0.56^{+0.01}_{-0.01}$	$4.9^{+1.8}_{-1.2} \times 10^{-4}$
0.1.....	0.73	Fe L xvii	$0.74^{+0.01}_{-0.02}$	$9.3^{+4.8}_{-5.3} \times 10^{-5}$
	0.74	O vii RRC		
0.1.....	0.87	O viii RRC	$0.86^{+0.02}_{-0.03}$	$9.6^{+4.1}_{-5.9} \times 10^{-5}$
0.1.....	0.90–0.92	Ne ix triplet	$0.92^{+0.03}_{-0.02}$	$1.4^{+0.3}_{-0.6} \times 10^{-4}$
0.1.....	1.02	Ne x Ly α	$1.01^{+0.01}_{-0.02}$	$7.6^{+3.0}_{-3.1} \times 10^{-5}$
0.1.....	1.07	Ne ix He β	$1.11^{+0.02}_{-0.02}$	$4.3^{+3.0}_{-3.1} \times 10^{-5}$
0.1.....	1.33–1.34	Mg xi triplet	$1.31^{+0.04}_{-0.05}$	$2.8^{+1.7}_{-1.9} \times 10^{-5}$
0.1.....	1.84–1.86	Si xiii triplet	$1.84^{+0.03}_{-0.04}$	$2.9^{+1.4}_{-1.4} \times 10^{-5}$
0.1.....	2.31–2.35	S ii–S x	$2.30^{+0.03}_{-0.04}$	$3.6^{+2.1}_{-2.1} \times 10^{-5}$
0.1.....	2.96–3.00	Ar ii–Ar xi	$2.85^{+0.15}_{-0.06}$	$1.8^{+1.3}_{-1.4} \times 10^{-5}$
0.1.....	6.40–6.97	Fe ii–Fe xxvi	6.40 ^b	$7.3^{+3.3}_{-3.3} \times 10^{-5}$
0.4.....	0.87	O viii RRC	0.86	2.2×10^{-4}
0.4.....	...	Artifact	1.54	-5.5×10^{-5}
0.4.....	1.73	Al xiii Ly α	1.72	2.5×10^{-5}
0.4.....	2.96–3.00	Ar ii–Ar xi	2.97	1.8×10^{-5}
0.4.....	6.40	Fe ii	6.40	4.3×10^{-5}
0.4.....	6.70	Fe xxv	6.80	5.5×10^{-5}
	6.97	Fe xxvi		

^a K : total photons $\text{cm}^{-2} \text{s}^{-1}$ in the line.

^b Fixed parameter.

Emission-line fluxes from the 0.4 s frame-time observation are listed in the lower portion of Table 2. Note that the line fluxes tabulated for the 0.4 s frame time are the new *total* fluxes of those lines that have changed or been added, and are *not* the difference in line flux between the 0.1 s and 0.4 s frame-time observations. The 0.4 s differ from the 0.1 s results in that: (1) the O viii RRC line is stronger (significantly above the 0.1 s frame-time error bars), (2) an Al line at 1.72 keV is probably present, (3) an “absorption” feature is seen at 1.54 keV that coincides with a sudden change in the effective area of the telescope, and is therefore probably caused by pile-up, (4) the Ar line better describes the data if it is shifted to 2.97 keV, and (5) the Fe line is resolved into a neutral (6.4 keV) and an ionized component (~ 6.80 keV), the normalization of their sum being consistent with the single Fe line seen in the 0.1 s frame-time data. The fluxes of the neutral and ionized components are comparable.

4.2. Northeast Region

The 0.4 s frame-time data do not suffer from pile-up in the northeast region, and have been used to determine both the shape of the continuum and the emission lines present. The 3.2 s data suffer from pile-up but have a higher signal-to-noise ratio and have been used where possible to investigate the X-ray emission lines, especially at higher energies.

4.2.1. Thermal Plasmas

The 0.4 s frame-time observations of the northeast region were initially modeled by an absorbed hot thermal plasma with solar metal abundances, using the MEKAL model in XSPEC. The MEKAL model does not provide a good description of the data (see Table 3) and can be ruled out. The model overproduces emission lines between 0.7 and 1.2 keV due to transitions to the L-shell of iron ions, and underproduces the high-energy continuum above a few keV. The addition of a second hot thermal plasma with

TABLE 3
SPECTRAL FITS TO THE NORTHEAST REGION FROM THE 0.4 s FRAME-TIME OBSERVATION

Model ^a	N_{H} ($\times 10^{20} \text{ cm}^{-2}$)	Temperature (keV)	Abundance ($Z_{\odot}$)	Normalization ^b	χ^2/dof
MEKAL	2.99 ^c	0.63	1.0	$K_{\text{MEKAL}} = 5.1 \times 10^{-4}$	4201/92
2 $\times$ MEKAL	2.99 ^c	0.21	1.00	$K_{\text{MEKAL}} = 7.8 \times 10^{-4}$	1780/90
		1.48	1.00	$K_{\text{MEKAL}} = 5.5 \times 10^{-4}$	1780/90
2 $\times$ Brem + lines	2.99 ^c	$0.39^{+0.02}_{-0.05}$		$K_{\text{Brem}} = 2.5^{+0.2}_{-0.1} \times 10^{-3}$	78/62
		$2.84^{+0.95}_{-0.41}$		$K_{\text{Brem}} = 1.2^{+0.8}_{-0.3} \times 10^{-4}$	78/62

^a Model abbreviations: MEKAL: Mewe, Kaastra, & Liedahl thermal plasma; PL: power law; Brem: bremsstrahlung.

^b The model normalization are $K_{\text{MEKAL}} = 10^{-14} \int n_e n_{\text{H}} dV / \{4\pi[(1+z)D_A]^2\}$, $K_{\text{Brem}} = 3.02 \times 10^{-15} \int n_e n_i dV / (4\pi D^2)$, and K_{PL} = photons $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$ at 1 keV; n_e is the electron density (cm^{-3}), n_{H} is the hydrogen density (cm^{-3}), n_i is the ion density (cm^{-3}), D is the distance to the source (cm), and D_A is the angular size distance to the source (cm).

^c Fixed parameter.

solar metal abundance improves the quality of the fit, but again does not provide a good description of the spectrum (Table 3).

4.2.2. Bremsstrahlung Plus Emission Lines

To further investigate the emission lines in the spectrum, the continuum was modeled by a smooth function consisting of two thermal bremsstrahlung components absorbed by the Galactic column. No physical meaning should be attributed to such a model, since an absorbed bremsstrahlung plus a power law model could have been used instead. Repeating the technique used to fit the spectrum of the nucleus, narrow emission lines were then added to the model. The *XMM-Newton* RGS spectrum (Paerels et al. 2000) was again used as a guide for the identification of the soft X-ray lines. As noted above, the spectral resolution of the ACIS is too low to provide unique identifications of the soft X-ray emission lines, many of which are blended together in our data below 1 keV. Two bremsstrahlung components with temperatures of 0.39 and 2.84 keV, plus the stronger emission lines seen by Paerels et al. (2000) and a line at 2.38 keV, all absorbed by the Galactic column, provides a good description of the spectrum with a χ^2 of 78 for 62 dof (bottom model of Table 3). The emission lines are listed in Table 4, and the spectrum and model are shown in Figure 8.

A single data bin at 0.5 keV (see Fig. 8) contributes significantly to the χ^2 of the fit and, if removed, the quality of fit is improved to $\chi^2 = 65$ for 61 dof. This data point is 9σ higher than its two neighbors over an energy range of 15 eV (Fig. 8). This is much narrower than the instrumental response, and the reason for this feature is unknown.

The line observed in the ACIS spectrum at 0.68 keV falls in the gap between strong lines of O VIII Ly α , Fe XVII, and the radiative recombination continua of N VII and O VII seen in the RGS spectrum, and has been attributed to a

FIG. 8.—X-ray spectrum of the northeast region (defined in § 2.2) of NGC 1068 extracted from the 0.4 s frame-time data. The top panel shows the data points with error bars (crosses), with the model folded through the instrument response (uppermost solid line passing through the data points). The individual components of the model are plotted below this. The lower panel shows the χ residuals to this fit. The parameters of this fit are listed in Tables 3 and 4. Note that the calibration is uncertain below 0.50 keV and degrades rapidly below 0.45 keV.

blurred combination of these. The line at an observed energy of 0.76 keV is close to O VIII Ly β seen in the RGS spectrum, and has been attributed to this transition. The small discrepancy in line energy may result from blending with the RRC of O VII at 0.74 keV. The line at 1.00 keV falls between strong lines of Fe XX and Ne X seen in the RGS spectrum and may represent a combination of these. The weak line at 2.38 keV corresponds to the K α transition of sulphur in the ionization range S X–S XIV.

The best-fit model to the 0.4 s frame-time data has an unabsorbed 0.5–2.0 keV flux of 1.6×10^{-12} ergs cm $^{-2}$ s $^{-1}$, corresponding to an unabsorbed rest-frame 0.5–2.0 keV

TABLE 4
X-RAY SPECTRAL LINES FROM THE NORTHEAST REGION

Frame Time (s)	Energy (keV)	Line	Observed Energy (keV)	K^a
0.4.....	0.37	C VI Ly α	$0.36^{+0.01}_{-0.01}$	$7.6^{+2.4}_{-2.5} \times 10^{-5}$
0.4.....	0.43	N VI triplet	$0.42^{+0.01}_{-0.01}$	$1.0^{+0.3}_{-0.3} \times 10^{-4}$
0.4.....	0.50	N VII	$0.52^{+0.01}_{-0.01}$	$7.1^{+1.6}_{-1.5} \times 10^{-5}$
0.4.....	0.59	N VII Ly β	$0.58^{+0.00}_{-0.00}$	$1.1^{+0.2}_{-0.1} \times 10^{-4}$
0.4.....	0.65	O VIII Ly α 7	$0.68^{+0.00}_{-0.01}$	$6.2^{+1.1}_{-1.1} \times 10^{-5}$
	0.67	N VII RRC		
	0.73	Fe L XVII		
	0.74	O VII RRC		
0.4.....	0.78	O VIII Ly β	$0.76^{+0.01}_{-0.01}$	$5.4^{+1.0}_{-1.2} \times 10^{-5}$
0.4.....	0.79–0.82	Fe XVII	$0.84^{+0.00}_{-0.01}$	$6.3^{+0.8}_{-1.2} \times 10^{-5}$
	0.82	O VIII Ly γ		
0.4.....	0.90–0.92	Ne IX triplet	$0.91^{+0.00}_{-0.01}$	$6.7^{+0.8}_{-0.9} \times 10^{-5}$
0.4.....	0.97 and 1.02	Fe XX and Ne X Ly α	$1.00^{+0.00}_{-0.01}$	$3.9^{+0.5}_{-0.7} \times 10^{-5}$
0.4.....	1.07	Ne IX He β	$1.08^{+0.01}_{-0.01}$	$2.0^{+0.5}_{-0.5} \times 10^{-5}$
0.4.....	1.21	Ne X Ly β	$1.19^{+0.01}_{-0.02}$	$9.7^{+3.3}_{-3.4} \times 10^{-6}$
0.4.....	1.35	Mg XI triplet	$1.35^{+0.01}_{-0.02}$	$7.9^{+2.9}_{-2.9} \times 10^{-6}$
0.4.....	1.80–1.86	Si X–Si XIII triplet	$1.82^{+0.02}_{-0.02}$	$7.6^{+2.2}_{-2.4} \times 10^{-6}$
0.4.....	2.35–2.43	S X–S XIV	$2.38^{+0.04}_{-0.03}$	$4.4^{+2.8}_{-2.8} \times 10^{-6}$
3.2.....	0.50	N VII	0.54	1.1×10^{-4}
	0.54	Artifact		
3.2.....	0.90–0.92	Ne IX triplet	0.91	1.2×10^{-4}
3.2.....	1.07	Ne IX He β	1.08	1.1×10^{-5}
3.2.....	6.40	Fe II	6.40	8.1×10^{-6}

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

TABLE 5
SPECTRAL FITS TO THE LARGER SCALE EXTENDED X-RAY EMISSION

Region	Model ^a	N_H ($\times 10^{20} \text{ cm}^{-2}$)	Abundance ($\times Z_\odot$)	Temperature (keV)	Photon Index	Normalization ^b	χ^2/dof
West	MEKAL	2.99 ^c	0.12	0.63	$0.13^{+0.63}_{-0.55}$	$K_{\text{MEKAL}} = 1.1 \times 10^{-3}$	481/122
	Brem + PL + lines	2.99 ^c		$0.73^{+0.04}_{-0.04}$		$K_{\text{Brem}} = 3.4^{+0.3}_{-0.1} \times 10^{-4}$ $K_{\text{PL}} = 2.9^{+8.5}_{-0.6} \times 10^{-6}$	102/89
North	MEKAL	2.99 ^c	0.01	0.41	$0.92^{+0.28}_{-0.19}$	$K_{\text{MEKAL}} = 9.5 \times 10^{-3}$	1554/140
	Brem + PL + lines	2.99 ^c		$0.36^{+0.01}_{-0.02}$		$K_{\text{Brem}} = 3.1^{+0.1}_{-0.1} \times 10^{-3}$ $K_{\text{PL}} = 1.7^{+1.2}_{-0.2} \times 10^{-5}$	106/92
East	MEKAL	2.99 ^c	0.06	0.57	$-0.21^{+0.68}_{-0.77}$	$K_{\text{MEKAL}} = 1.2 \times 10^{-3}$	328/108
	Brem + PL + lines	2.99 ^c		$0.53^{+0.03}_{-0.04}$		$K_{\text{Brem}} = 3.9^{+0.3}_{-0.2} \times 10^{-4}$ $K_{\text{PL}} = 1.6^{+3.9}_{-0.7} \times 10^{-6}$	88/73
South	MEKAL	2.99 ^c	0.09	0.75	$-0.20^{+0.07}_{-0.06}$	$K_{\text{MEKAL}} = 1.5 \times 10^{-3}$	1228/156
	Brem + PL + lines	2.99 ^c		$1.06^{+0.05}_{-0.05}$		$K_{\text{Brem}} = 3.3^{+0.1}_{-0.1} \times 10^{-4}$ $K_{\text{PL}} = 4.7^{+1.7}_{-0.5} \times 10^{-6}$	144/118

^a Model abbreviations: MEKAL: Mewe, Kaastra, & Liedahl thermal plasma; PL: power law; Brem: bremsstrahlung.

^b The model normalization are $K_{\text{MEKAL}} = 10^{-14} \int n_e n_H dV / \{4\pi[(1+z)D_A]^2\}$, $K_{\text{Brem}} = 3.02 \times 10^{-15} \int n_e n_I dV / (4\pi D^2)$, and $K_{\text{PL}} = \text{photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$ at 1 keV; n_e is the electron density (cm^{-3}), n_H is the hydrogen density (cm^{-3}), n_I is the ion density (cm^{-3}), D is the distance to the source (cm), and D_A is the angular size distance to the source (cm).

^c Fixed parameter.

luminosity of $1.0 \times 10^{41} \text{ ergs s}^{-1}$, and an unabsorbed 2.0–10.0 keV flux of $2.0 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$, corresponding to an unabsorbed rest-frame 2.0–10.0 keV luminosity of $1.2 \times 10^{40} \text{ ergs s}^{-1}$.

The 3.2 s frame-time data suffer from pile-up, so we followed the same procedure as was used for the 0.4 s frame-time observation of the nucleus. The pile-up fraction was estimated to be 46%, but this is uncertain since the extraction region is not a point source, as was assumed in modeling the pile-up. The continuum parameters are different from those found for the 0.4 s frame data; the cooler bremsstrahlung component is 0.1 keV warmer, and the hotter bremsstrahlung is 6.5 keV warmer. The significantly higher temperature of the latter component may be a result of the larger energy range of the 3.2 s frame-time data; i.e., the continuum model is required to produce significant X-ray flux at higher energies. The emission-line fluxes from the 3.2 s frame-time data are listed at the bottom of Table 4. Again, note that the tabulated line fluxes are the *total* line fluxes and not the differences in flux between the 3.2 and 0.4 s frame-time data. The changes are as follows: (1) the N VII line has a preferred energy of 0.54 keV, which corresponds to a sudden change in the effective area of the telescope, and is therefore probably caused by pile-up; (2) the Ne IX triplet is stronger; (3) the Ne IX He β line is weaker; and (4) an Fe line is tentatively detected, but its energy is poorly constrained.

4.3. Larger Scale Emission

4.3.1. Thermal Plasmas

We followed a procedure similar to that used for the nucleus and northeast region, applying it to the west, north, east, and south regions in turn. The 3.2 s frame-time observations were used, since they have the longest exposure time and do not suffer from pile-up. A hot plasma absorbed by the Galactic column does not provide a good description of the data from any of these regions, even if the metal abundances are allowed to vary (see Table 5). The preferred values of the metal abundances are very low (less than 12% solar), and the thermal model does not fit the significant hard X-ray emission seen from each region above 2 keV. We conclude that a single-temperature thermal plasma

model, absorbed by the Galactic column, cannot describe the spectrum in any of the larger scale extended regions.

4.3.2. Bremsstrahlung Plus Power-Law Plus Emission Lines

The phenomenological approach described in § 4.1.2 was again used to study the emission lines from each of these regions. The continuum was described by a smooth model consisting of a bremsstrahlung plus power law, both absorbed by the Galactic column, to which individual emission lines were then added. The parameters of the continuum fits are listed in Table 5, and the emission lines listed in Tables 6 (west), 7 (north), 8 (east), and 9 (south). The spectrum and models are shown in Figures 9 (west), 10 (north), 11 (east), and 12 (south). Good fits were obtained with bremsstrahlung components with temperatures in the range 0.36–1.06 keV and power laws with photon indices in the range $\Gamma = -0.21$ to 0.92, with the harder (lower) photon

FIG. 9.—X-ray spectrum of the west region (defined in § 2.3) of NGC 1068 extracted from the 3.2 s frame-time data. The top panel shows the data points with error bars (*crosses*), with the model folded through the instrument response (*uppermost solid line passing through the data points*). The individual components of the model are plotted below this. The bottom panel shows the χ residuals to this fit. The parameters of this fit are listed in Tables 5 and 6. Note that the calibration is uncertain below 0.50 keV and degrades rapidly below 0.45 keV. The four large diagonal crosses with horizontal bars represent estimates of the contributions in the indicated energy bands from the bright, inner ($r < 5''$) emission, which has been scattered by the telescope PSF (see § 4.3.2).

TABLE 6
X-RAY SPECTRAL LINES FROM THE WEST REGION

Energy (keV)	Line	Observed Energy (keV)	K^a
0.37	C vi Ly α	$0.33^{+0.02}_{-0.01}$	$1.6^{+1.5}_{-0.6} \times 10^{-5}$
0.56–0.57	O vii triplet	$0.57^{+0.00}_{-0.01}$	$2.4^{+0.4}_{-0.3} \times 10^{-5}$
0.65	O viii Ly α	$0.66^{+0.01}_{-0.00}$	$3.0^{+0.4}_{-0.2} \times 10^{-5}$
0.67	N vii RRC		
0.74	O vii RRC and Fe xvii	$0.74^{+0.01}_{-0.01}$	$3.7^{+0.2}_{-0.2} \times 10^{-5}$
0.77	O viii Ly β	$0.80^{+0.01}_{-0.01}$	$3.5^{+0.3}_{-0.3} \times 10^{-5}$
0.78	Fe l xviii		
0.81 and 0.82	Fe l xvii		
0.87	O viii RRC	$0.87^{+0.00}_{-0.01}$	$2.8^{+0.3}_{-0.3} \times 10^{-5}$
0.90–0.92	Ne ix triplet	$0.92^{+0.01}_{-0.00}$	$2.7^{+0.2}_{-0.7} \times 10^{-5}$
1.02	Ne x Ly α	$1.01^{+0.01}_{-0.00}$	$2.2^{+0.2}_{-0.2} \times 10^{-5}$
1.07	Ne ix He β	$1.11^{+0.00}_{-0.02}$	$5.4^{+1.1}_{-1.3} \times 10^{-6}$
1.23	Na xi Ly α	$1.23^{+0.01}_{-0.02}$	$4.4^{+0.9}_{-1.2} \times 10^{-6}$
1.33–1.34	Mg xi triplet	$1.33^{+0.01}_{-0.01}$	$4.7^{+1.0}_{-0.9} \times 10^{-6}$
1.47	Mg xii Ly α	$1.44^{+0.03}_{-0.03}$	$1.3^{+0.4}_{-0.7} \times 10^{-6}$
1.84–1.86	Si xii–Si xiii triplet	$1.85^{+0.01}_{-0.01}$	$3.8^{+0.9}_{-0.7} \times 10^{-6}$
2.31–2.41	S ii–S xiii	$2.36^{+0.05}_{-0.04}$	$1.1^{+0.8}_{-0.6} \times 10^{-6}$
6.40–6.97	Fe ii–Fe xxvi	6.40^b	$2.1^{+1.2}_{-1.1} \times 10^{-6}$

^a K : total photons $\text{cm}^{-2} \text{s}^{-1}$ in the line.

^b Fixed parameter.

indices in the south and east regions. There is significant hard X-ray emission above 2 keV from each region, and an iron line is seen from the west, north, and south regions. The unabsorbed broadband fluxes and luminosities are listed in Table 10.

The energy-dependent PSF of the *Chandra* mirrors will scatter a fraction of the flux from the nucleus and northeast region over tens of arcseconds, and this can significantly contaminate the spectra of the larger scale extended emission regions. In particular, the wings of the PSF are stronger at higher energies, and it is important to assess the

reliability of the hard X-ray emission seen on the larger scales. First, the spectra show hard ($\gtrsim 3$ keV) X-ray fluxes differing by a factor of ~ 3 –4 between the east (the weakest) and south (the strongest) regions (see Figs. 11 and 12, respectively). In the regions between 23'5 and 60' a similar difference in hard X-ray flux is also seen (Fig. 13), with stronger emission from the west and south. Since the PSF is essentially circularly symmetric, these must be due to differences in the intrinsic spectra of these regions. Second, images of the extended hard X-ray emission (e.g., Fig. 6), are clearly not circularly symmetric with the strongest emission

TABLE 7
X-RAY SPECTRAL LINES FROM THE NORTH REGION

Energy (keV)	Line	Observed Energy (keV)	K^a
0.37	C vi Ly α	$0.38^{+0.00}_{-0.01}$	$1.2^{+0.1}_{-0.1} \times 10^{-4}$
0.43	N vi triplet	$0.43^{+0.01}_{-0.01}$	$5.3^{+1.0}_{-1.1} \times 10^{-5}$
0.52	N vi He γ	$0.52^{+0.01}_{-0.00}$	$5.8^{+0.7}_{-0.8} \times 10^{-5}$
0.56–0.57	O vii triplet	$0.57^{+0.01}_{-0.00}$	$1.0^{+0.1}_{-0.1} \times 10^{-4}$
0.67	N vii RRC and O viii Ly α	$0.68^{+0.00}_{-0.01}$	$4.9^{+0.5}_{-0.5} \times 10^{-5}$
0.74	O vii RRC and Fe xvii	$0.75^{+0.01}_{-0.00}$	$3.2^{+0.4}_{-0.4} \times 10^{-5}$
0.81 and 0.82	Fe xvii	$0.83^{+0.01}_{-0.01}$	$3.5^{+0.4}_{-0.3} \times 10^{-5}$
0.82	O viii Ly γ		
0.90–0.92	Ne ix triplet	$0.90^{+0.00}_{-0.01}$	$5.0^{+0.3}_{-0.4} \times 10^{-5}$
~ 0.95	Fe l xx	$0.95^{+0.01}_{-0.01}$	$3.1^{+0.6}_{-0.6} \times 10^{-5}$
1.02	Ne x Ly α	$1.03^{+0.00}_{-0.00}$	$1.9^{+0.3}_{-0.1} \times 10^{-5}$
1.15	Ne ix He γ	$1.14^{+0.01}_{-0.01}$	$7.5^{+1.6}_{-1.8} \times 10^{-6}$
1.23	Na xi Ly α	$1.22^{+0.01}_{-0.01}$	$4.6^{+1.7}_{-1.2} \times 10^{-6}$
1.33–1.34	Mg xi triplet	$1.34^{+0.01}_{-0.01}$	$7.8^{+1.4}_{-1.3} \times 10^{-6}$
1.47	Mg xii Ly α	$1.47^{+0.02}_{-0.03}$	$1.6^{+0.9}_{-0.9} \times 10^{-6}$
1.74–1.77	Si ii–Si viii	$1.76^{+0.01}_{-0.02}$	$3.4^{+1.0}_{-1.1} \times 10^{-6}$
1.82–1.86	Si xi–Si xiii triplet	$1.83^{+0.01}_{-0.01}$	$5.0^{+0.8}_{-1.0} \times 10^{-6}$
2.00	Si xiv	$1.97^{+0.02}_{-0.03}$	$1.8^{+0.7}_{-0.7} \times 10^{-6}$
2.31–2.37	S ii–S xi	$2.35^{+0.02}_{-0.02}$	$2.9^{+0.9}_{-0.9} \times 10^{-6}$
2.46	S xv triplet	$2.49^{+0.02}_{-0.03}$	$1.4^{+0.7}_{-0.7} \times 10^{-6}$
3.01–3.14	Ar xii–Ar xvii triplet	$3.06^{+0.05}_{-0.04}$	$1.0^{+0.7}_{-0.6} \times 10^{-6}$
3.84–4.11	Ca xvii–Ca xx	$3.93^{+0.04}_{-0.08}$	$8.1^{+5.8}_{-5.7} \times 10^{-7}$
6.40–6.97	Fe ii–Fe xxvi	$6.32^{+0.05}_{-0.03}$	$2.6^{+1.4}_{-1.4} \times 10^{-6}$

^a K : total photons $\text{cm}^{-2} \text{s}^{-1}$ in the line.

TABLE 8
X-RAY SPECTRAL LINES FROM THE EAST REGION

Energy (keV)	Line	Observed Energy (keV)	K^a
0.43	N vi triplet	$0.41^{+0.01}_{-0.02}$	$7.9^{+4.9}_{-4.6} \times 10^{-6}$
0.50	N vii	$0.52^{+0.02}_{-0.01}$	$8.4^{+3.0}_{-4.0} \times 10^{-6}$
0.59	N vii Ly α	$0.59^{+0.01}_{-0.01}$	$1.9^{+0.3}_{-0.5} \times 10^{-5}$
0.65	N vii RRC	$0.67^{+0.01}_{-0.01}$	$2.0^{+0.2}_{-0.4} \times 10^{-5}$
0.73	Fe xvii	$0.73^{+0.01}_{-0.01}$	$2.0^{+0.4}_{-0.3} \times 10^{-5}$
0.81 and 0.82	Fe xvii	$0.80^{+0.02}_{-0.02}$	$2.1^{+0.2}_{-0.4} \times 10^{-5}$
0.82	O viii Ly δ		
0.87	O viii RRC	$0.85^{+0.02}_{-0.00}$	$1.7^{+0.2}_{-0.5} \times 10^{-5}$
0.90–0.92	Ne ix triplet	$0.91^{+0.01}_{-0.00}$	$2.0^{+0.3}_{-0.5} \times 10^{-5}$
1.02	Ne x	$1.01^{+0.00}_{-0.01}$	$1.2^{+0.1}_{-0.2} \times 10^{-5}$
1.07	Ne ix He β	$1.08^{+0.01}_{-0.02}$	$3.8^{+1.1}_{-1.1} \times 10^{-6}$
1.15	Ne ix He γ	$1.15^{+0.02}_{-0.02}$	$2.6^{+0.9}_{-0.7} \times 10^{-6}$
1.30–1.35	Mg viii–Mg xi triplet	$1.32^{+0.01}_{-0.02}$	$3.1^{+0.9}_{-1.1} \times 10^{-6}$
1.35	Mg xi triplet	$1.37^{+0.02}_{-0.03}$	$1.1^{+0.7}_{-0.7} \times 10^{-6}$
1.48	Mg xii Ly α	$1.47^{+0.02}_{-0.03}$	$7.8^{+6.0}_{-5.7} \times 10^{-7}$
1.78–1.84	Si ix–Si xii	$1.81^{+0.01}_{-0.02}$	$2.0^{+0.6}_{-0.6} \times 10^{-6}$
1.87–2.00	Si xiii–Si xiv	$1.93^{+0.03}_{-0.03}$	$1.0^{+0.5}_{-0.5} \times 10^{-6}$
2.35–2.46	S x–S xv	$2.38^{+0.06}_{-0.03}$	$1.2^{+0.6}_{-0.6} \times 10^{-6}$

^a K : total photons $\text{cm}^{-2} \text{s}^{-1}$ in the line.

in the large-scale regions seen in the south and west sectors. This strongly suggests that scattering of nuclear emission by the circularly symmetric PSF cannot account for all of this emission. An “iron line” image was constructed by taking the 6.3–6.5 keV iron line band and subtracting normalized 5.8–6.3 and 6.5–7.0 keV continuum band images. The resulting distribution of discrete counts from the iron line extends $\sim 20''$ to the northeast and southwest, and at lower surface brightness $\sim 50''$ to the west and south. This agrees well with the hard X-ray flux and iron lines seen in the spectra of the extended and far-extended regions (Figs. 9–12 and Fig. 13).

To quantify the effects of scattering by the PSF, the following approach was used. Four images were constructed in which the central circular region of radius $5''$ contained the observed distribution of emission in the bands 0.25–0.40, 1.10–1.90, 3.56–5.46, and 5.46–7.34 keV. Outside this radius (which corresponds to the inner border of the large-scale regions), the emission was set to zero. These images were then convolved with PSFs computed at 0.23, 1.50, 3.51, and 6.40 keV respectively, using the CIAO tool *mkarf*. From the convolved images, the predicted count rate per keV due to telescope scattering from the inner bright region can be obtained for each of the larger scale extended

TABLE 9
X-RAY SPECTRAL LINES FROM THE SOUTH REGION

Energy (keV)	Line	Observed Energy (keV)	K^a
0.37	C vi	$0.37^{+0.01}_{-0.01}$	$2.2^{+0.8}_{-1.0} \times 10^{-5}$
0.43	N vi triplet	$0.43^{+0.01}_{-0.01}$	$2.0^{+0.5}_{-0.7} \times 10^{-5}$
0.50	N vii	$0.50^{+0.01}_{-0.01}$	$1.3^{+0.4}_{-0.5} \times 10^{-5}$
0.56	O vii triplet	$0.56^{+0.01}_{-0.00}$	$4.0^{+0.6}_{-1.2} \times 10^{-5}$
0.67	N vii RRC and O viii Ly α	$0.67^{+0.00}_{-0.01}$	$3.7^{+0.3}_{-1.9} \times 10^{-5}$
0.72	O vii RRC and Fe xvii	$0.74^{+0.00}_{-0.01}$	$4.3^{+0.4}_{-1.3} \times 10^{-5}$
0.79–0.82	Fe xvii	$0.80^{+0.07}_{-0.04}$	$3.3^{+0.5}_{-1.6} \times 10^{-5}$
0.77–0.82	O viii Ly β , γ		
0.79–0.82	O viii Ly α and Fe xvii	$0.84^{+0.02}_{-0.04}$	$3.3^{+0.5}_{-1.0} \times 10^{-5}$
0.90–0.92	Ne ix triplet	$0.90^{+0.00}_{-0.01}$	$4.0^{+0.3}_{-2.0} \times 10^{-5}$
0.97	Fe xx	$0.96^{+0.01}_{-0.00}$	$1.9^{+0.2}_{-0.3} \times 10^{-5}$
1.02	Ne x Ly α	$1.03^{+0.01}_{-0.00}$	$2.1^{+0.2}_{-0.2} \times 10^{-5}$
1.15	Ne ix He γ	$1.12^{+0.01}_{-0.01}$	$7.1^{+1.5}_{-1.5} \times 10^{-6}$
1.21	Ne x Ly β	$1.21^{+0.01}_{-0.01}$	$8.1^{+1.3}_{-1.5} \times 10^{-6}$
1.35	Mg xi triplet	$1.33^{+0.00}_{-0.01}$	$1.0^{+0.1}_{-0.1} \times 10^{-5}$
1.47	Mg xii Ly α	$1.45^{+0.02}_{-0.02}$	$2.6^{+0.9}_{-1.0} \times 10^{-6}$
1.74–1.77	Si ii–Si viii triplet	$1.74^{+0.02}_{-0.01}$	$3.0^{+1.0}_{-0.9} \times 10^{-6}$
1.82–1.86	Si xi–Si xiii triplet	$1.83^{+0.01}_{-0.01}$	$5.6^{+1.0}_{-1.1} \times 10^{-6}$
2.39–2.46	S xii–S xv triplet	$2.42^{+0.02}_{-0.03}$	$1.9^{+1.8}_{-0.9} \times 10^{-6}$
6.40	Fe ii	6.40^b	$5.1^{+1.7}_{-1.6} \times 10^{-6}$

^a K : total photons $\text{cm}^{-2} \text{s}^{-1}$ in the line.

^b Fixed parameter.

FIG. 10.—X-ray spectrum of the north region (defined in § 2.3) of NGC 1068 extracted from the 3.2 s frame-time data. The top panel shows the data points with error bars (crosses), with the model folded through the instrument response (uppermost solid line passing through the data points). The individual components of the model are plotted below this. The bottom panel shows the χ residuals to this fit. The parameters of this fit are listed in Tables 5 and 7. Note that the calibration is uncertain below 0.50 keV and degrades rapidly below 0.45 keV. The four large diagonal crosses with horizontal bars represent estimates of the contributions in the indicated energy bands from the bright, inner ($r < 5''$) emission, which has been scattered by the telescope PSF (see § 4.3.2).

regions. These are the four horizontal bars plotted in Figures 9–13. There is clear evidence of an excess of hard X-ray emission from the north and south regions, and tentative evidence from the west, whereas the hard X-ray flux from the east region may have been scattered from the nucleus by the telescope mirrors. Restricting our attention to the more distant regions between $23''.5$ and $60''$ (Fig. 13), we find evidence of excess hard X-ray emission from the west and south regions, and possibly the north.

4.4. The Spatial Distribution of the Absorbing Column

Spectra containing at least 800 counts were extracted from square regions of the 3.2 s frame-time *Chandra* data, allowing the absorbing column density to each region to be determined. Each spectrum was modeled by an absorbed MEKAL plasma with variable metal abundance over the energy range 0.25–3.00 keV. The resulting map of absorbing column density over the face of the galaxy is shown in Figure 14. The southwest side of the galaxy shows absorption in excess of the Galactic column [$N_{\text{H}}(\text{Gal}) = 2.99 \times 10^{20} \text{ cm}^{-2}$], whereas the northeast side shows no significant excess absorption. This result shows that the extended X-ray emission to the northeast of the nucleus is on the near

FIG. 11.—X-ray spectrum of the east region (defined in § 2.3) of NGC 1068 extracted from the 3.2 s frame-time data. The top panel shows the data points with error bars (crosses), with the model folded through the instrument response (uppermost solid line passing through the data points). The individual components of the model are plotted below this. The bottom panel shows the χ residuals to this fit. The parameters of this fit are listed in Tables 5 and 8. Note that the calibration is uncertain below 0.50 keV and degrades rapidly below 0.45 keV. The four large diagonal crosses with horizontal bars represent estimates of the contributions in the indicated energy bands from the bright, inner ($r < 5''$) emission, which has been scattered by the telescope PSF (see § 4.3.2).

side of the galactic disk of NGC 1068, while that to the southwest is either in the galactic disk or on its far side. This geometrical arrangement agrees with indications from both the high-excitation ionized gas seen at optical wavelengths and radio continuum observations. The ionized gas to the northeast is much stronger than that to the southwest, a difference usually attributed to excess obscuration on the southwest side (e.g., Baldwin, Wilson, & Whittle 1987; Evans et al. 1991). Furthermore, the northeast radio lobe is strongly polarized, while that to the southwest is unpolarized (Wilson & Ulvestad 1983, hereafter WU83), consis-

FIG. 12.—X-ray spectrum of the south region (defined in § 2.3) of NGC 1068 extracted from the 3.2 s frame-time data. The top panel shows the data points with error bars (crosses), with the model folded through the instrument response (uppermost solid line passing through the data points). The individual components of the model are plotted below this. The bottom panel shows the χ residuals to this fit. The parameters of this fit are listed in Tables 5 and 9. Note that the calibration is uncertain below 0.50 keV and degrades rapidly below 0.45 keV. The four large diagonal crosses with horizontal bars represent estimates of the contributions in the indicated energy bands from the bright, inner ($r < 5''$) emission, which has been scattered by the telescope PSF (see § 4.3.2).

TABLE 10

FLUXES AND LUMINOSITIES OF THE LARGER SCALE
EXTENDED X-RAY EMISSION

Region	Energy Band (keV)	Unabsorbed Flux (ergs cm ⁻² s ⁻¹)	Unabsorbed Luminosity (ergs s ⁻¹)
West	0.5–2.0	5.8×10^{-13}	3.6×10^{40}
West	2.0–10.0	2.3×10^{-13}	1.4×10^{40}
North...	0.5–2.0	1.4×10^{-12}	8.7×10^{40}
North...	2.0–10.0	3.3×10^{-13}	2.0×10^{40}
East	0.5–2.0	4.1×10^{-13}	2.5×10^{40}
East	2.0–10.0	2.0×10^{-13}	1.2×10^{40}
South ...	0.5–2.0	7.8×10^{-13}	4.9×10^{40}
South ...	2.0–10.0	6.6×10^{-13}	4.0×10^{40}

FIG. 13.—Spectra of the west, north, east and south sectors (see Fig. 1), but including only the annuli between radii $23''.5$ and $60''$. In each panel, the model is a variable metallicity MEKAL plasma plus a power law. The four large diagonal crosses with horizontal bars represent estimates of the contributions in the indicated energy bands from the bright, inner ($r < 5''$) emission, which has been scattered by the telescope PSF (see § 4.3.2).

FIG. 14.—Contours of the 0.25–7.50 keV X-ray emission from the 3.2 s frame-time observation superposed on a map of the inferred absorbing column density to the soft X-ray emission (*gray scale*). Contours are plotted at 1, 2, 4, 8, 16, 32, 64, 128, 256, and 512 counts per pixel. The lowest contour levels are close to the noise, so counts have been averaged in blocks of 2×2 pixels. The column density is seen to be larger to the southwest of the nucleus than to the northeast.

tent with the southwest lobe being depolarized by gas in the galaxy disk. Finally, H I 21 cm absorption observations indicate unambiguously that the northeast radio lobe is located in front of the galaxy disk and the southwest radio lobe is behind it (Gallimore et al. 1994).

5. COMPARISON WITH OBSERVATIONS IN OTHER WAVEBANDS

5.1. Registration of Images

NGC 1068 contains considerable structure within the central arcsecond. There are several radio components arranged in a “bent linear” structure (e.g., WU83; Ulvestad, Neff, & Wilson 1987; Muxlow et al. 1996; Gallimore et al. 1996b; Gallimore, Baum, & O’Dea 1997; Roy et al. 1998). There is also structure in optical emission line and continuum images obtained with the *Hubble Space Telescope* (HST) (e.g., Evans et al. 1991; Macchetto et al. 1994), and in both near- and mid-infrared band images obtained at the diffraction limit of large ground-based telescopes (e.g., Weinberger, Neugebauer, & Matthews 1999; Bock et al. 2000).

The location of the true nucleus (meaning the putative black hole and its accretion disk) has been much discussed. Radio source S1 has a flat or inverted spectrum (Gallimore et al. 1996b), which may originate through thermal emission from the inner edge of the obscuring torus (Gallimore et al. 1996a; Roy et al. 1998). VLBA imaging (Gallimore et al. 1997) shows that this source is a parsec-sized disk of ionized gas. Source S1 is also the location of water maser emission,

indicative of dense molecular gas (Claussen & Lo 1986; Greenhill et al. 1996). To within measurement errors, radio source S1 is coincident with the peaks of mid-infrared (Braatz et al. 1993) and near-infrared (Thatte et al. 1997) light, and probably with the center of symmetry of the polarization pattern of scattered UV light (Capetti et al. 1995; Kishimoto 1999). There is thus a general consensus that these features mark the location of the true nucleus.

There is, however, no particular reason why the peak of X-ray emission should coincide with this location. The column density, N_H , to the X-ray nucleus of NGC 1068 exceeds $\sim 10^{25} \text{ cm}^{-2}$ (e.g., Matt et al. 2000), so all the X-ray emission we observe must be either intrinsically extended or scattered nuclear light. The *Chandra* astrometry is not currently accurate enough for a precise location of the nucleus with respect to the subarcsecond-scale features described in the previous paragraph. The position of the peak of the broadband X-ray emission, as measured by the 0.4 s frame-time exposure, is $\alpha_X(\text{J2000}) = 02^{\text{h}}42^{\text{m}}40^{\text{s}}.71$, $\delta_X(\text{J2000}) = -00^{\circ}00'47''.7$. This position is remarkably close to that of the brightest radio source in the nucleus at 5 GHz (Muxlow et al. 1996): $\alpha_r(\text{J2000}) = 02^{\text{h}}42^{\text{m}}40^{\text{s}}.715$, $\delta_r(\text{J2000}) = -00^{\circ}00'47''.64$. The difference in each coordinate is less than $0''.1$. This agreement is considerably better than expected given *Chandra*'s current absolute astrometric errors, and may thus be coincidental. Nevertheless, we decided to align the peak in the *Chandra* image with the peak in a 5 GHz radio map with $0''.4$ resolution (WU83), which is similar to, although somewhat better than, the resolution of the *Chandra* image. Simulations showed that smoothing the 60 mas resolution 5 GHz map of Muxlow et al. (1996) to the $0''.4$ resolution of the WU83 map moves the radio peak slightly to the northeast (by $\leq 0''.1$ in each coordinate), to $\alpha_{rs}(\text{J2000}) = 02^{\text{h}}42^{\text{m}}40^{\text{s}}.721$, $\delta_{rs}(\text{J2000}) = -00^{\circ}00'47''.55$. This position agrees to $\leq 0''.1$ with the actual position of the peak in the WU83 map after precessing the original B1950.0 coordinates of that map to J2000.0 using the facility in the DS9 display program.

Thus, for purposes of comparison with observations in other wavebands, the peak in the broadband *Chandra* image was assigned the coordinates α_{rs} , δ_{rs} given above. In order to extend the astrometric comparison to optical images, we used the alignment between the optical and radio emissions obtained by Capetti, Macchetto, & Lattanzi (1997b). These authors obtained absolute astrometry for the *HST* images by taking three images: a photographic refractor plate, a ground-based CCD image, and an *HST* image. The plate covered astrometric standard stars from which astrometric positions were obtained for many fainter, secondary astrometric reference stars, some of which are on the CCD image. Finally, the astrometric scale of the *HST* image was registered to the ground-based CCD image by a cross-correlation technique. From this procedure, the location of the peak of emission in the *HST* optical continuum (filter F547M) image is found to be $\alpha_o(\text{J2000}) = 02^{\text{h}}42^{\text{m}}40^{\text{s}}.711$, $\delta_o(\text{J2000}) = -00^{\circ}00'47''.81$ (Capetti et al. 1997b). This position is also very close to the *Chandra*-measured location of the X-ray peak: $\alpha_X - \alpha_o = 0''.015$, $\delta_X - \delta_o = 0''.15$, which represents agreement given the *Chandra* errors.

We emphasize that this astrometric registration between the X-ray image on the one hand and the radio and optical images on the other is not precise and may change as the *Chandra* astrometry improves. However, this uncertainty only affects the alignment on subarcsecond scales, such as is needed to compare the *Chandra* image with *HST* and radio interferometric data. Spatial comparisons on larger scales (i.e., greater than $1''$) are robust. In the following discussion, we compare the X-ray morphology with that in the optical line, optical continuum, and radio continuum.

5.2. Comparison with Optical Emission-Line Images

Figure 15 shows the X-ray emission (contours) superposed on an *HST* image taken through filter F502N; this image is dominated by $[\text{O III}] \lambda 5007$. There is remarkable agreement between the structures in the two wavebands. To

FIG. 15.—Superposition of the circumnuclear distribution of X-rays on an *HST* image taken through filter F502N (Dressel et al. 1997; Capetti et al. 1997a); this image is dominated by the light of $[\text{O III}] \lambda 5007$. The images were aligned as described in § 5.1. The X-ray image (contours) represents photon events in the energy range 0.25–7.5 keV taken from the 0.4 s frame-time observation at the full *Chandra* resolution. The cross marks the position of radio source S1, which is believed to coincide with the nucleus (§ 5.1). *Left*: Contours are plotted on a logarithmic scale at $\log(\text{counts pixel}^{-1}) = 0.5, 1.0, 1.5, 2.0, 2.5$, and 3.0. The gray scale is proportional to the square root of the intensity and ranges from 1×10^{-18} (white) to 1×10^{-16} (black) $\text{ergs cm}^{-2} \text{s}^{-1} (\text{PC pixel})^{-1}$. *Right*: An enlarged view of the circumnuclear region. Contours are plotted on a logarithmic scale at $\log(\text{counts pixel}^{-1}) = 0.3, 0.6, 0.9, 1.2, 1.5, 1.8, 2.1, 2.4, 2.7, 3.0$. The gray scale is proportional to the logarithm of the intensity and ranges from 1×10^{-17} (white) to 1×10^{-13} (black) $\text{erg cm}^{-2} \text{s}^{-1} (\text{PC pixel})^{-1}$. A close association is seen between many structures in the two wavebands.

the south of the nucleus (assumed to be radio source S1, marked by the cross) and within $2''$ of it (Fig. 15, *right*), the structure in both wavebands is aligned approximately north-south (P.A. $\simeq 13^\circ$), and there are detailed correspondences between the two images. To the north of the nucleus, both structures bend toward higher P.A., reaching P.A. $\simeq 35^\circ$ some $4''$ from the nucleus. It is notable that the bright extension of the X-rays corresponds closely to the bright emission-line clouds that extend from the nucleus to $\sim 2''$ northeast of it (Fig. 15, *right*). There is also a close correspondence between the brightnesses slightly farther ($6''$) from the nucleus, where the X-ray contours take a V-shaped form, with apex toward the northeast (see also Figs. 17 and 18).

Correspondences are also seen on the larger scale shown in Figure 15 (*left*). Some $7''$ northeast of the nucleus, there is a prominent narrow feature in the *HST* image that first extends north and then curves toward the northwest, ending up extending in P.A. $\sim 287^\circ$ when $10''$ from the nucleus. The X-ray ridge, although observed with lower resolution, follows this feature closely. An armlike feature in the *HST* image begins some $4''$ southeast of the nucleus and curves toward lower P.A., extending toward the northeast and ending up some $6''$ – $7''$ east of the nucleus; the X-ray contours follow it closely. Various other close correspondences between the faint [O III] and X-ray emission are also visible in Figure 15 (*left*).

Similar correspondences are seen between the X-ray emission and the *HST* image through filter F658N (Fig. 16), which is dominated by $H\alpha + [\text{N II}] \lambda\lambda 6548, 6583$. The relative intensities of the various line features are different in this band (e.g., the narrow feature beginning $7''$ northeast is much weaker here than in [O III]), but there is still a close association between the structures in the two wavebands.

A comparison between [O III] $\lambda 5007$ and X-ray emission on a larger scale is shown in Figure 17. The bottom panel shows again the extension from the nucleus to the northeast, which is common to the two images. The overall shape of the outer X-ray contours is similar to the [O III] (*top panel*). To the southwest, there are two spiral arms that

curve outward in a clockwise sense (i.e., they trail the galactic rotation). The inner, brighter one is some $18''$ and the outer, fainter one some $28''$ from the nucleus. In both cases, there is a remarkably precise alignment with the X-ray contours (*top panel*). The stronger, X-ray point sources are not seen in the [O III] image; this is not surprising if they are X-ray binaries in NGC 1068.

5.3. Comparison with Optical Continuum Images

Figure 18 shows the *Chandra* X-ray contours superposed on a red continuum image (from Pogge & De Robertis 1993). Features common to both images include a protrusion $7''$ – $8''$ southwest of the nucleus and, as described in the previous subsection, the two spiral arms southwest of the nucleus and the armlike feature southeast and east of the nucleus. However, on the largest scales on which X-ray emission is seen, the X-ray image is much more elongated than the optical. There is little or no X-ray emission seen more than $30''$ from the nucleus in the southeast or northwest directions, while the X-rays extend much farther to northeast and southwest. The impression gained from these comparisons with optical data is that the X-rays correlate more strongly with the optical line than with the optical continuum emission.

This absence of a close correlation between the X-ray and optical continuum images strongly suggests that the starburst disk is not the dominant source of the extended X-ray emission.

5.4. Comparison with Radio Continuum Images

As noted in § 5.1, radio continuum images with sub-arcsecond resolution reveal a “bent linear” structure extending over $1''.5$. Although the *Chandra* image of the central regions (e.g., Fig. 15) does not have good enough resolution for a meaningful comparison, the extension of the X-ray emission immediately to the south of the nucleus is more or less north-south, like the radio emission. North of the nucleus, the X-ray ridge line “bends” toward the northeast, as does the radio emission. Capetti et al. (1997b) show that this arcsecond-scale radio structure lies in a

FIG. 16.—Superposition of the circumnuclear distribution of X-rays on an *HST* image taken through filter F658N (Dressel et al. 1997; Capetti et al. 1997a); this image is dominated by the light of $H\alpha + [\text{N II}] \lambda\lambda 6548, 6583$. The images were aligned as described in § 5.1. The X-ray image (contours), the contour levels, and the cross are the same as in Fig. 15. *Left*: Gray scale is proportional to the square root of the intensity and ranges from 1×10^{-18} (white) to 2×10^{-16} (black) $\text{ergs cm}^{-2} \text{s}^{-1} (\text{PC pixel})^{-1}$. *Right*: An enlarged view of the circumnuclear region. The gray scale is proportional to the logarithm of the intensity and ranges from 1×10^{-17} (white) to 1×10^{-13} (black) $\text{ergs cm}^{-2} \text{s}^{-1} (\text{PC pixel})^{-1}$. As for the [O III] $\lambda 5007$ image (Fig. 15), there are clear associations between structures in the two wavebands.

FIG. 17.—Superposition of the *Chandra* 3.2 s frame-time data with events in the range 0.25 to 7.5 keV (contours) on an image in the velocity-integrated [O III] $\lambda 5007$ line (gray scale) taken with the Taurus Fabry-Perot instrument on the AAT (G. Cecil 2000, private communication). The images were aligned as described in § 5.1, and the cross marks the position of radio source S1, which is believed to coincide with the nucleus (§ 5.1). The “hole” at the nucleus in the X-ray image is not real but results from pile-up (§ 2). The X-ray image has been smoothed with a Gaussian function of standard deviation $\sigma = 0.5$. The resolution (seeing) of the [O III] image is 1.0 (FWHM), very similar to that of the smoothed *Chandra* image. The X-ray image is contoured at 1, 2, 4, 8, 16, 32, 64, 128, 256, and 512 counts (pixel) $^{-1}$ in both panels. The gray scale is proportional to the logarithm of the number of counts per pixel in both panels, and the two panels differ only in the scaling of the gray scale. In the top panel, it ranges from log counts pixel $^{-1} = 0.5$ (white) to 1.3 (black) and in the bottom from log counts pixel $^{-1} = 0.5$ (white) to 4 (black).

region of relatively low optical line emission and is surrounded by emission-line clouds. As argued by many authors (e.g., Wilson & Willis 1980; Wilson, Ward, & Haniff 1988; Evans et al. 1991; Macchetto et al. 1994; Gallimore et al. 1996), the structure of the narrow-line region implies compression of interstellar gas by the radio ejecta. Thus, given the close association between the X-rays and the narrow-line region (§ 5.2), the alignment between the X-rays and the arcsecond-scale radio structure is expected.

A comparison between the X-ray (gray scale) and radio (contours) images on a larger scale is shown in Figure 19. The V-shaped, edge-brightened radio lobe to the northeast, which may represent a blast wave driven into the interstellar gas by the radio ejecta (Wilson & Ulvestad 1987), is seen to be associated with bright X-ray emission. The X-ray image also exhibits a V-shaped structure with apex some $6''$

FIG. 18.—Superposition of the *Chandra* 3.2 s frame-time data with events in the range 0.25 to 7.5 keV (contours) on an optical continuum image taken through a filter with center wavelength/bandwidth 6100/200 Å (gray scale; Pogge & De Robertis 1993). The images were aligned as described in § 5.1, and the cross marks the position of radio source S1, which is believed to coincide with the nucleus (§ 5.1). The “hole” at the nucleus in the X-ray image is not real but results from pile-up (§ 2). The resolution of the optical image is $0.5''$ – $0.6''$. The *Chandra* image has been smoothed with a Gaussian function of standard deviation $\sigma = 0.5$ and is contoured at 1, 2, 4, 8, 16, 32, 64, 128, 256, and 512 counts pixel $^{-1}$. The gray scale of the optical image is proportional to the square root of the intensity between 1 (white) and 2000 counts pixel $^{-1}$ (black). Notable correlations between the two images are apparent.

FIG. 19.—Superposition of the circumnuclear distribution of X-rays (gray scale) on a VLA 6 cm radio map (contours) with resolution $0.38'' \times 0.38''$ (Wilson & Ulvestad 1983). The images were aligned as described in § 5.1. The X-ray image is the same as shown in Fig. 3. The cross marks the position of radio source S1, which is believed to coincide with the nucleus (§ 5.1). Contours are plotted at 0.0005, 0.001, 0.002, 0.004, 0.008, 0.032, 0.128, and 0.256 Jy beam $^{-1}$. The gray scale is proportional to the logarithm of the X-ray intensity and ranges between log counts pixel $^{-1} = 0$ (black) and 3.0 (white).

from the nucleus (see also Figs. 15 and 17). This structure is obviously connected with the radio “V,” but has a wider opening angle. This last difference may result, in part, from the lower resolution of the X-ray image. To the southwest of the nucleus, the X-rays are much weaker, consistent with the higher absorbing column to the X-ray-emitting gas found here (§ 4.4). Nevertheless, the brighter regions of radio emission in the southwest lobe do appear to be associated with brighter X-ray emission. There is little or no enhancement of the X-ray emission at the radio “hot spot” 4.0 southwest of the nucleus.

6. CONCLUSIONS

We have obtained the highest resolution ($<1''$) image to date of the X-ray emission of NGC 1068. This image shows (1) a bright nucleus close to or coincident with the brightest radio and optical emission, (2) bright emission extending $\approx 5''$ (550 pc) to the northeast, (3) large-scale structure reaching at least $1'$ (6.6 kpc) to the northeast and southwest, including X-ray emission from spiral arms, and (4) numerous point sources, most of which are likely to be associated with NGC 1068.

X-ray spectra have been obtained for ten regions: the nucleus, the bright region several arcseconds to the northeast, four 90° sectors between $5''$ and $60''$ from the nucleus, and four similar sectors between $23.5''$ and $60''$ from the nucleus. Hot plasma models are poor descriptions of the spectra, and the best approximations require implausibly low ($\lesssim 0.1 Z_\odot$) abundances. We have constructed models of the spectra comprising two smooth continua (a bremsstrahlung plus a power-law or two bremsstrahlung spectra) plus emission lines. The lines cannot be uniquely identified with the present spectral resolution but are generally consistent with the stronger lines seen in the *XMM-Newton* RGS spectrum below 2 keV (Paerels et al. 2000). Above 2 keV we observe $K\alpha$ transitions of sulfur, argon, and iron. Hard X-ray emission, including an iron line, is seen extending $\sim 20''$ (2.2 kpc) northeast and southwest of the nucleus. Lower surface brightness hard X-ray emission, with a tenta-

tively detected iron line, extends $\sim 50''$ (5.5 kpc) to the west and south. Taken together with the *XMM-Newton* RGS spectrum, our results suggest photoionization and fluorescence of gas by radiation from the Seyfert nucleus to several kiloparsecs from it.

An investigation of the distribution of absorbing column shows that the emission to the northeast of the nucleus is absorbed by only the Galactic column and is thus on the near side of the disk of NGC 1068. The X-ray emission to the southwest of the nucleus suffers greater absorption and must originate in or behind the disk of NGC 1068. This geometry agrees with that inferred for both the narrow-line region observed at optical wavelengths and the radio ejecta.

We have compared the X-ray image with optical emission-line, optical continuum, and radio continuum images. There is a very strong correlation between the X-ray emission and high-excitation optical line emission (as traced by $[O\text{ III}] \lambda 5007$), consistent with photoionization in both wavebands. To the southwest, the X-ray spiral arms correlate closely with those seen in $[O\text{ III}] \lambda 5007$. The northeast radio lobe some $6''$ (660 pc) from the nucleus shows a strong morphological correlation with the X-ray emission, suggestive of interstellar gas being compressed by the radio ejecta. The alignment of the large-scale (arcminute) and small-scale (few arcsecond) X-ray emissions and the lack of a close correlation between the larger scale X-ray emission and the optical continuum strongly suggests that the starburst is not the dominant source of these X-rays.

We plan to present a discussion of the compact X-ray sources seen in NGC 1068 and a more detailed analysis of the extended emission in future papers.

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