SIMULTANEOUS CHANDRA AND ROSSI X-RAY TIMING EXPLORER OBSERVATIONS OF THE NEARBY BRIGHT SEYFERT 2 GALAXY NGC 4945

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ABSTRACT

We analyze recent simultaneous Chandra/RXTE observations of the Seyfert 2 galaxy NGC 4945. The unprecedented spatial resolution of Chandra means we are able to separate the spectra of the nucleus, starburst, and superwind regions, while the RXTE data extend the spectrum to higher energies. The extreme absorbing column of $N_H \sim 4 \times 10^{24} \text{ cm}^{-2}$ means that the nucleus is only directly seen above 8–10 keV, while the lower energy spectrum from the nuclear region in Chandra is dominated by reflection. By contrast, the superwind is dominated by emission from hot plasma, but the starburst region contains both hot plasma and reflection signatures. Forming a reflected spectrum requires that the starburst region contain clumps of cool, optically thick material, perhaps star-forming cores, which are irradiated by 7–10 keV photons from the nucleus. Since photons of this energy are obscured along the line of sight, this confirms the result of Madejski et al. that the extreme absorption material is disklike rather than toroidal. However, the IR/optical limits on the lack of high-excitation emission lines show that, by contrast, the lower energy photons from the nucleus are obscured in all directions. We discuss the complex absorption structure revealed by these observations and propose an overall source geometry in which the nucleus is completely embedded in material with $N_H \sim 10^{23} \text{ cm}^{-2}$.

Subject headings: galaxies: individual (NGC 4945) — galaxies: Seyfert — X-rays: galaxies

On-line material: color figures

1. INTRODUCTION

Our best current picture of Seyfert 2 galaxies relies on the unified scheme, in which all the main ingredients of the nucleus—black hole, accretion disk, and broad-line region—are identical in all active galaxies, and the classification depends on the orientation with respect to the line of sight. There is a small-scale, geometrically thin accretion disk around the black hole, while at distances larger than ~1 pc there is a geometrically thick molecular torus. The material in the disk and torus provides intrinsic obscuration, such that for the viewing directions intersecting the disk and/or torus, the intrinsic emission of the active galactic nucleus (AGN) is modified by the absorbing material. In particular, the light from the broad optical/UV emission lines is obscured by dust, while photoelectric absorption by gas and dust gives a low-energy cutoff in the soft X-ray emission. The magnitude of the absorption depends on the column density of material in the line of sight. For columns of $N_H > 10^{23} \text{ cm}^{-2}$, the central engine can be completely obscured, though some small fraction of the intrinsic nuclear light can be seen as a result of electron scattering by low-density ionized gas; this gas would be located around the axis of symmetry of the system, both within the torus and in the form of a wind emanating from the nucleus.

Such a picture is broadly consistent with a range of observed optical, X-ray, radio, and polarization properties of Seyfert 1 and 2 galaxies (see, e.g., the review by Veron-Cetty & Veron 2000), but these data are generally indirect, as they do not resolve any of the structures proposed. One of the nearest AGNs of any kind—and thus the most appropriate for a detailed study of the spatial structure to test these unified models—is the nearby (3.7 Mpc; Mauersberger et al. 1996) Seyfert 2 galaxy NGC 4945. Spatial studies are further aided by the strong absorption, with an equivalent hydrogen column density of $\sim 4 \times 10^{24} \text{ cm}^{-2}$ (Iwasawa et al. 1993; Done, Madejski, & Smith 1996; Madejski et al. 2000), corresponding to $\tau_{\text{Thomson}} \sim 2.4$. With this column, the nuclear X-ray flux at energies corresponding to the Fe L and Kα lines is entirely absorbed, so the measured line fluxes originate in the scatterer or in the obscuring medium, yet above ~10 keV, the nuclear power law dominates the spectrum. In fact, it is the brightest Seyfert 2 galaxy above 20 keV, as measured by OSSE (Done et al. 1996), RXTE (Madejski et al. 2000), and BeppoSAX (Guainazzi et al. 2000). The hard X-ray emission is rapidly variable on time-scales of about a day or less, implying that the Thomson-thick absorption is probably confined to a structure that is geometrically rather thin, i.e., more probably associated with the disk rather than the torus (Madejski et al. 2000). Importantly, NGC 4945 is an H2O megamaser source (Dos Santos & Lepine 1979), which traces underlying cool, dense molecular structures probably within ~1 pc of the central engine. Unlike NGC 4258, this emission does not give the
smooth rotation curve expected from a well-ordered disk but, assuming this irregular, clumpy distribution still traces orbital motion, gives an estimate of the central mass of $\sim 1.4 \times 10^6 \, M_\odot$ (Greenhill, Moran, & Herrnstein 1997). Knowing the intrinsic X-ray luminosity and the mass of the central source allows an estimate of the accretion rate in Eddington units of 10% (Greenhill et al. 1997; Madejski et al. 2000) and aids in detailed dynamical studies of the source.

The ionized material filling the opening of the torus also emits recombination line and continuum radiation, generally resulting in strong Fe L and Kα lines (Krolik & Kallman 1987; Band et al. 1990). However, despite this theoretical work there is comparatively little known about the scattering region in Seyfert 2 galaxies. This is mainly due to spatial confusion, as Seyfert nuclei often coexist with nuclear starbursts/superwind activity, and these contribute to the soft X-ray emission and Fe L lines. This is certainly the case for NGC 4945 (Heckman, Armus, & Miley 1990; Nakai 1989). To disentangle the effects of the scattering region from the starburst and superwind, we need high spatial resolution, provided by the superior angular resolution available with Chandra.

In this paper, we report on the Chandra imaging observations of the nuclear region of NGC 4945. These have already been published by Schurch, Roberts, & Warwick (2002), but here we do a much more detailed spatially resolved analysis. We also include simultaneous data from RXTE in order to constrain the direct nuclear spectrum and present a plausible interpretation regarding the geometry of the source, which fits with both the IR/optical and X-ray constraints.

2. OBSERVATIONS

2.1. Chandra

The Chandra data were taken on 2000 January 27–28 with the ACIS camera in the faint mode for a total of 49 ks, with the nucleus focused on the S3 chip. The filtered file produced by standard processing was further cleaned by running the software tool acisscreen and gain corrected using acisgaincorr.1 These cleaned data from the S3 chip were screened to reject periods of high background (defined as times at which the total count rate of events labeled as valid was greater than 20 counts per second), and the resulting image of NGC 4945 with exposure of 38 ks is shown in Figure 1. The image clearly shows a pointlike emission coincident with the megamaser source, and a diffuse "plume"

1 ACIS tools are available at http://lheawww.gsfc.nasa.gov/users/kaa/xselect/chandra.html.

![Chandra image of NGC 4945](image-url)
extending roughly in the northwest direction from the nucleus, which is perpendicular to the plane defined by the megamaser emission of the galaxy, which in turn is closely aligned with the plane of the host galaxy. We perform spectral analysis of various regions of that image separately as described below.

The nuclear spectrum (hereafter “nuc”) was extracted from a circle of radius 4 pixels (2”) centered on the brightest spot. The nearby diffuse emission was taken from a box surrounding this region, excluding a circle of radius 4.5 pixels centered on the nucleus (hereafter “diff-nuc”). Further diffuse emission spectra were taken from two regions shown overlaid on Figure 1, hereafter “diff-1” and “diff-2.” A background spectrum was taken from a nearby, source-free region. The response and auxiliary files were created for the nuclear region using acismakermf, acisarfprep, and mkarf, and these files were used for all spectra. For the subsequent analysis, we grouped all extracted spectra such that there were at least 20 total counts per new bin.

2.2. RXTE PCA and HEXTE

The simultaneous RXTE data were extracted using the rex script, with the epoch 4 faint source background models. This resulted in a total of 60 ks of PCA data from layer 1, detectors 0 and 2. As in the previous RXTE observations of this object, the source counting rate is rather modest, with source counts being less than 10% of the background.

We know from previous observations that the nucleus of NGC 4945 is a relatively hard X-ray source, where the primary, nuclear emission can be well described as a heavily absorbed power law. Since we are mainly interested in the RXTE PCA data regarding the nuclear component, we present the PCA light curve in the 8–30 keV band (channels 19–69) in Figure 2, with contiguous orbits giving even sampling of the light curves on timescales of a few thousand seconds, spanning a total of ~1.5 days. This extends the variability seen in the previous monitoring campaign, which had single orbit snapshots once per day for ~1.5 months (Madejski et al. 2000). Plainly there is considerable variability power in this object on timescales shorter than 1 day.

The HEXTE data from clusters 0 and 1 were also extracted with the rex script, and here the background is even more dominant. Nonetheless, the variability seen in the PCA and HEXTE are consistent with each other (Fig. 3). Since the method of background estimation is very different in the PCA (blank field predictions) and HEXTE (offset pointings), this shows that the majority of the variability seen is indeed connected to the source rather than to background uncertainties. We use the HEXTE data from 20–100 keV and allow for a normalization offset between this and the PCA.

3. NUCLEAR SPECTRUM

3.1. Chandra

The superb imaging capabilities of Chandra allow an extraction of the spectrum from the nuclear source alone. This spectrum is shown in Figure 4 and is clearly dominated by iron Kα line emission, but also includes a hard broadband continuum. We fit this with an absorbed power law and iron line and find that the nuclear continuum is indeed extremely hard, with Γ = −0.9, and that the (narrow, σ fixed at 10 eV) line at 6.4 keV has a large equivalent width (EW) of 1.3 keV (χ² = 66.0/51).

The fit can be significantly improved if the line is broad or if it consists of a number of components. Allowing the line to be broad we obtain χ² = 47.9/50 with σ = 0.09+/−0.03 keV, and the EW increases to 2 keV with intensity 2.0 ± 0.4 × 10⁻⁵ photons s⁻¹. Alternatively, adding a second, narrow line at 6.5 keV (fixed energy) gives χ² = 48.3/50 and EW of 570 and 270 eV for the 6.4 and 6.5 keV components, respectively. Repeating the fits to ungrouped data, using C-statistics, gives (for 1043 PHA bins) C-stat = 929 for a narrow Gaussian at 6.38 keV.
obtain the reflection model, is shown in Figure 4. There is a marginally significant residual ($\Delta \chi^2 = 5$ for 2 additional degrees of freedom) for a narrow line at energy $6.73 \pm 0.08$, which could indicate the presence of reflection from more highly ionized material.

The deconvolved spectrum with the unsmeared reflection model is shown in Figure 4. There is a marginally significant residual ($\Delta \chi^2 = 5$ for 2 additional degrees of freedom) for a narrow line at energy $6.73 \pm 0.08$, which could indicate the presence of reflection from more highly ionized material.

3.2. Broadband Nuclear Spectrum

Figure 5 shows the broad band nuclear spectrum derived from fitting the nuclear spectrum from Chandra, together with the PCA and HEXTE data. Chandra can spatially resolve the nuclear emission in the 1–10 keV range, but both the PCA and HEXTE data cover a large field of view ($\sim 1 \times 1 \text{deg}^2$), so include a contribution from off-nuclear point sources and host galaxy diffuse emission as well as the nucleus itself. We fit the spectra from the three instruments simultaneously, but include a contribution from extended emission in the PCA and HEXTE spectra that is set to zero in the Chandra data. This extended emission can be well fitted by a hot plasma (modeled here using a solar abundance MEKAL code), and we also include an additional emission line at 6.4 keV. The nuclear emission is modeled by a heavily absorbed power law and its weakly absorbed reflection ($pexrav$ plus a Gaussian line), and results are detailed in Table 1. The overall shape of the spectrum is very similar to that seen in previous observations, and a direct comparison of the PCA spectrum with that of Madejski et al. (2000) shows no evidence for any changes in spectral shape, but the absorbed power-law emission from the nucleus is a factor of 1.8 brighter in the observations reported here.

The PCA spectrum contains much more line emission than seen in Chandra. While much of this is consistent with moderately ionized (6.5–6.7 keV) emission from the hot diffuse plasma, there is also evidence for an additional line at 6.4 keV, implying a contribution to the fluorescent emission from the extended region (see also Guainazzi et al. 2000, Schurch et al. 2002, and § 4 below).

The heavy absorption toward the nucleus implies that the obscuring material is optically thick to electron scattering, with an optical depth of a few. This scattering changes the spectral shape from that obtained by pure absorption, and we model this using the Monte Carlo code of Krolik. 

\footnote{$pexrav$ is a model within the XSPEC spectral fitting package.}
Maduawi & Życki (1994). Motivated by previous and current observations in which the rapid variability implies a rather geometrically thin (disklike) absorbing structure, we assume that the absorbing material subtends a rather small solid angle to the X-ray source (Madejski et al. 2000). We also replace the separate reflection continuum/absorption/reflection models with iron alone at twice solar abundance. The line EW can be produced, but also increases the opacity so fewer line photons produced, even at the iron edge that can produce the fluorescence line above the iron edge. However, increasing the abundances of the heavy elements—this increases the amount of line produced, but also increases the opacity so fewer line photons escape (George & Fabian 1991). However, increasing the iron abundance relative to the other elements can give a marked change in the line EW (George & Fabian 1991), and fits to the Chandra/RXTE full nuclear continuum using absorption/reflection models with iron alone at twice solar abundance give a significantly worse fit than those using solar abundances. Iron overabundances are predicted in most chemical evolution models for AGN and are often observed (Haman & Ferland 1993). However, there is a delay of ~1–2 Gyr for the onset of the Fe-producing Type Ia supernovae, so our observed solar abundances are consistent with models for a young starburst (0.01 Gyr) in this object (Marconi et al. 2000).

### 3.3. Origin of the Nuclear 6.4 keV Fe K Line

Clearly, one of the main questions is the origin of the Fe K line. In the model of the nuclear spectrum above, the line can arise either in the reflector or in the optically thick absorbing material. This distinction may be somewhat artificial, as it is possible to envisage a geometry in which the absorber and reflector are the same structure, e.g., where we are looking at an absorbing disk at an angle closer to 80° (the assumed opening angle) rather than 90° so reflected photons from the far side of the disk can be seen without being absorbed. Any warp on the disk will also enhance the solid angle of reflecting material that can be seen, and it is noteworthy that the maser emission in this and other AGNs indicates that the cool material at 0.1–1 pc has a shallow warp.

In our assumed geometry, where we view the absorbing disk/torus at 90°, this material produces ~25% of the total line seen from the nucleus. The separate reflecting material produces the rest of the line, and for solar abundances, the EW of the line to reflected continuum is about 1.3–1.6 keV (George & Fabian 1991; Matt, Perola, & Piro 1991). This is not strongly affected by increasing the abundances of all the heavy elements—this increases the amount of line produced, but also increases the opacity so fewer line photons escape (George & Fabian 1991). However, increasing the iron abundance relative to the other elements can give a marked change in the line EW (George & Fabian 1991), and fits to the Chandra/RXTE full nuclear continuum using absorption/reflection models with iron alone at twice solar abundance give a significantly worse fit than those using solar abundances. Iron overabundances are predicted in most chemical evolution models for AGN and are often observed (Haman & Ferland 1993). However, there is a delay of ~1–2 Gyr for the onset of the Fe-producing Type Ia supernovae, so our observed solar abundances are consistent with models for a young starburst (0.01 Gyr) in this object (Marconi et al. 2000).

Our reflection model assumes that the iron line is produced in optically thick material. However, the line EW can also be affected by the column density of the material. The reflection models assume that the material is optically thick, i.e., $N_H \geq 2 \times 10^{24}$ cm$^{-2}$. At these columns, all the photons above the iron edge that can produce the fluorescence line are absorbed. If the column is reduced below $\sim 10^{23}$ cm$^{-2}$, this is no longer true. The material becomes thin to the photoelectric absorption opacity at the iron edge, and the line decreases. However, this also changes the reflected continuum—depending on the geometry it can either look like a standard reflection spectrum up to the point where the material becomes optically thin to photoelectric opacity, or it can look like straightforward absorption by a column of

### Table 1

| Parameter                  | Value                  |
|----------------------------|------------------------|
| $N_H^a$ (cm$^{-2}$)        | $4.25 \pm 0.25 \times 10^{22}$ |
| $\Gamma$                   | $1.65 \pm 0.15$        |
| Norm                       | 0.03                   |
| $N_H^b$ (cm$^{-2}$)        | $0.8 \pm 0.8 \times 10^{22}$ |
| $f_{\text{ion}} [\text{Fe}]$ | $6 \pm 2 \times 10^{-8}$ |
| Fe K intensity$^b$ (photons cm$^{-2}$ s$^{-1}$) | $2.0 \pm 0.5 \times 10^{-5}$ |
| $\chi^2$/dof              | 105.5/111$^a$           |

Notes:
- $^a$ Absorption applied to the intrinsic nuclear (power-law) spectrum.
- $^b$ Absorption applied to all spectral components.

There is also a MEKAL plasma ($kT = 5.3^{+2.0}_{-1.1}$ keV, 2–10 keV unabsorbed flux of $5 \times 10^{30}$ ergs s$^{-1}$) and additional 6.4 keV narrow Gaussian line with intensity $2.3\pm0.5$ photons cm$^{-2}$ s$^{-1}$ in the PCA and HETEX data (normalizations set to zero in Chandra) so as to account for the extended emission in their wide fields of view.
10^{23} \text{ cm}^{-2}. Given that the observed continuum in Chandra looks like optically thick reflection up to at least 6–7 keV, the column density of the reflecting material must be at least 10^{23} \text{ cm}^{-2}.

4. DIFFUSE EMISSION

The Chandra spectra from the diffuse emission regions extracted from regions located at progressively farther distances from the nucleus are shown in Figure 7. The nuclear spectrum itself is shown for comparison in the top panel. Plainly the diffuse spectra nearby the nucleus (diff-nuc and diff-1) contain a substantial iron Kα line and show a hard continuum spectrum, which suggests that they are also dominated by Compton reflection from optically thick material at high energies. However, the increasing counts at low energy and increasing strength of line features (such as the ~1.8 keV line, presumably due to He-like silicon, and the iron L emission lines) show that there is also an increasing fraction of the emission from hot/photoionized plasma as distance from the nucleus increases. This hot plasma could be either predominantly photoionized by the nucleus or mechanically heated by the starburst. In either case it will contain some free electrons that scatter some fraction of the nuclear light, giving an additional scattered power-law component.

We assume the intrinsic primary emission is an isotropically emitted power law with fixed index 1.85 and normalization of 2.79 photons cm^{-2} s^{-1} at 1 keV, as derived from § 3.2. Some fraction, \( f_{\text{refl}} \), of this is reflected from cold material (again we use the reflection code in which the self-consistent iron line emission is included), while another fraction, \( f_{\text{scatt}} \), is scattered from hot electrons, forming a power law.

We first assume that the line emission is from a mechanically heated plasma (using the MEKAL code), and these fits are detailed in Table 2. We also include fits to the Chandra nuclear spectrum, to show the limits on the scattered and hot gas emission on the smallest scales, though here we truncate the data at 6.6 keV so as not to include any transmitted flux. With this different energy range the line broadening is much less significant, at \( \Delta \chi^2 = 3 \).

The data show clear differences in the absorbing column, decreasing as a function of distance from the nucleus. The ISM in our galaxy in this direction has \( N_{\text{H}} \sim 2 \times 10^{21} \text{ cm}^{-2} \) while the observed column is significantly higher than this in all fields except diff-2. This is unsurprising, as NGC 4945 is an edge-on galaxy. The Chandra nuclear spectrum is inferred to be ~5 times more absorbed in these fits than from the reflection model fitting in § 3.1. This is due both to the steeper illuminating spectrum and to ignoring the data above 6.6 keV, which include a component from the direct nuclear emission. Intriguingly, CO observations imply a ring of molecular gas with column of ~7 x 10^{22} \text{ cm}^{-2} in the nuclear direction (Whiteoak et al. 1990), and photoelectric absorption is known to follow the molecular gas column in Seyfert 2 galaxies (e.g., Wilson et al. 1998).

The data also indicate that the different spectral components behave differently with distance from the nucleus. The neutral reflected fraction is highest in the nucleus, then is

| File       | \( N_{\text{H}} \) (x 10^{22} \text{ cm}^{-2}) | \( kT \) (keV) | MEKAL Flux (ergs s^{-1} \text{ cm}^{-2}) | \( f_{\text{scatt}} \) | \( f_{\text{refl}} \) | \( \chi^2/\text{dof} \) |
|------------|---------------------------------------------|---------------|------------------------------------------|-----------------|-----------------|-----------------|
| nuc............ | 7.1^{+2.9}_{-2.1}                          | 0.7^e         | 2.4^{+4.4}_{-2.4} \times 10^{-12}         | 0^{+0.8}_{-0.8} \times 10^{-5} | 1.2^{+0.8}_{-0.8} \times 10^{-3} | 51.6/43         |
| diff-nuc...... | 3.8^{+1.3}_{-1.2}                          | 0.7^e         | 3.4^{+6.6}_{-3.4} \times 10^{-13}         | 1.8^{+0.6}_{-0.6} \times 10^{-5} | 4.1^{+1.1}_{-1.1} \times 10^{-4} | 35.8/39         |
| diff-1 ....... | 1.8 ± 0.2                                 | 0.71 ± 0.11   | 1.0^{+0.4}_{-0.4} \times 10^{-12}         | 3.4^{+0.4}_{-0.4} \times 10^{-6} | 4.5^{+0.5}_{-0.5} \times 10^{-4} | 62.5/62         |
| diff-2 ....... | 0.32^{+1.1}_{-0.7}                         | 0.68 ± 0.08   | 1.0^{+0.1}_{-0.1} \times 10^{-13}         | 5.1 ± 1.2 \times 10^{-6} | 6.5^{+0.5}_{-0.5} \times 10^{-7} | 60.2/76         |

\( ^{a} \) Foreground absorption applied to all model components.
\( ^{b} \) Bolometric, unabsorbed flux extrapolated over 0.01–100 keV.
\( ^{c} \) Normalization relative to that of the primary known from the broadband modeling.
\( ^{d} \) Normalization in units of \( \Omega/2(\pi) \). Assumes inclination 60°.
\( ^{e} \) Temperature fixed at 0.7 keV as the component is not significantly detected.
and 230 pc, so the ionization parameter,
\[ \frac{\gamma}{\Gamma} \]

tered fractions derived from the fits, except for diff-2. The fit
regions
2000), and the \[ \text{Fe} \text{II} \]
mid-IR (Genzel et al. 1998; Marconi et al. 2000; Spoon et al.
illuminating the extended emission in any other waveband.

the path length
\[ D \]

10, or photoionization will dominate over colli-
strongly clumped, so that its density is higher by a factor of

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The self consistency of this model can be checked by esti-
mating the density of the MEKAL plasma diffuse emission,
and then using this to calculate how important photoioniza-
tion should be. The luminosity of a MEKAL plasma of den-
sity \( n \) in volume \( V \) is \( \Delta n^2 V \), where \( \Delta \sim 3 \times 10^{-22} \text{ ergs cm}^3 \text{ s}^{-1} \) for a temperature of \( \sim 1 \text{ keV} \). The three regions, diff-nuc, diff-1, and diff-2, have volumes of \( \sim 5 \times 10^{61}, 7 \times 10^{61}, \) and \( 10^{63} \text{ cm}^3 \), respectively (assuming axial symmetry), so the hot plasma densities are \( \sim 1.7, 0.5, \) and \( 0.07 \text{ cm}^{-3} \), assuming it
smoothly fills the volume. In our model this hot gas also
scatters the direct nuclear flux. The scattered fraction \( f_{\text{scatt}} = \Omega/(4\pi)\tau = \Omega/(4\pi)n_{\text{scatt}} D \Delta r \), where the solid angle \( \Omega/4\pi \sim 1, 0.27, \) and 0.16 for diff-nuc, diff-1, and diff-2, and the path length \( D \Delta r \sim 30, 86, \) and 350 pc. The scattered fractions predicted by the hot plasma are \( \sim 10^{-4}, 2.3 \times 10^{-5}, \) and \( 8 \times 10^{-6} \). These are significantly bigger than the scattered fractions derived from the fits, except for diff-2. The fit result scattered fractions predict densities of \( \sim 0.3, 0.05, \) and \( 0.06 \text{ cm}^{-3} \), respectively, for plasma smoothly filling the volume.

The distance \( r \) from the nucleus in each case is \( \sim 50, 93, \) and 230 pc, so the ionization parameter, \( \xi = L/(n r^2) \), is approximately constant at \( \sim 2000 \) in each region. This high value indicates that the model of collisionally heated hot gas filling the volume is not self-consistent. Either the gas is strongly clumped, so that its density is higher by a factor of more than 10, or photoionization will dominate over colli-
sional equilibrium. A key problem with having photoioniza-
tion dominate is that there are no signatures of the AGN illuminating the extended emission in any other waveband.

There are no standard AGN high-excitation narrow lines in the optical (e.g., [O iii]: Moorwood et al. 1996), near-
mid-IR (Genzel et al. 1998; Marconi et al. 2000; Spoon et al.
2000), and the [Fe ii]/Br \( \gamma \) line ratios are indicative of shock heating rather than photoionization (Reunanen, Kotilai-
en, & Prieto 2002). The observed extended emission line regions must be shielded from the nuclear photoionizing flux (5 eV–1 keV; Marconi et al. 2000), but the extended 6.4 keV line emission shows that it must be illuminated by photons \( \geq 7 \text{ keV} \). Hence the nucleus must be absorbed by columns of \( \geq 10^{22} \text{ cm}^{-2} \) in all directions.

Photoionization by such a hard (absorbed) X-ray spec-
trum would lead to fluorescence lines from mostly neutral material rather than ionized line emission. This is observed in the extended 6.4 keV Fe line emission (significantly detected in diff-nuc and diff-1), but this cannot explain the lower energy line emission (e.g., Si at 1.8 keV or the iron L complex in diff-1 and diff-2). Thus the low-energy lines must be from collisionally ionized material, so the MEKAL parameters derived above indicate that the material must be clumpy.

The requirement that the nuclear spectrum be absorbed means that the model of a power law for the scattered flux is also not consistent. Replacing this by an absorbed power
law gives stringent constraints in diff-2. Absorption of \( N_{\text{H}} \sim 1.4 \times 10^{23} \) on the scattered flux increases \( \chi^2 \) by 2.7, while columns of \( 10^{22} \) and \( 10^{23} \text{ cm}^{-2} \) increase it by 8.5 and 12.5, respectively. Thus, it seems most likely that the 3–5 keV continuum is not from scattered nuclear flux but rather is from hot, clumped gas.

Models of starburst galaxies indicate that the material is indeed strongly clumped (Suchkov et al. 1996; Strickland & Stevens 2000), such that multiphase and multitemperature gas exists at all radii. We replace the scattered component with a second, higher temperature MEKAL plasma. This gives similar \( \chi^2 \) fits to all the spectra, but requires temperatures of 4–7 keV in addition to the lower temperature gas at 0.5–0.7 keV. Such hot gas is difficult to produce (Suchkov et al. 1994; Strickland & Stevens 2000), but this component is observed in pure starburst galaxies (Pietsch et al. 2001), and a similar model with multitemperature hot components was used by Schurch et al. (2002) to fit the diffuse emission in both Chandra and XMM-Newton. An alternative explanation could be that it is from an unresolved population of X-ray binaries (Persic & Rephaeli 2002).

To summarize, all the off-nuclear spectra require that the gas be multiphase. The most likely interpretation is that they all have multitemperature clumps of hot gas, while diff-
nuc and diff-1 also strongly require the presence of cool, optically thick clumps.

5. THE OVERALL GEOMETRY

The Chandra image can be superposed on previous images of this galaxy at other wavelengths. Our diff-nuc spectrum corresponds to the 100–200 pc edge-on starburst ring traced by molecular gas (Br \( \gamma \): Moorwood et al. 1996; Pa\( \alpha \) and H\( \alpha \): Marconi et al. 2000; CO: Curran et al. 2001). This ring has its major axis along the major axis of the host galaxy (northeast-southwest direction), which also matches the position angle of the central maser disk (Greenhill et al. 1997).

The diff-1 spectrum extends into the region of molecular gas where the emission is dominated by H\( \alpha \) rather than by Pa\( \alpha \) (Marconi et al. 2000). The Pa\( \alpha \) line traces mainly star-
burst activity, while the H\( \alpha \) emission probably reflects shock heating on the edges of the superwind cone (Moorwood et al. 1996). The diff-2 spectrum covers the extended narrow line emission seen as a cone in the low-excitation lines H\( \alpha \) and [N ii] (Moorwood et al. 1996).

The extreme absorption seen toward the nucleus in X-rays corresponds to optical depths of \( \sim 2.5 \) to electron scattering. This material has a rather small scale height, as otherwise the scattered X-rays would noticeably smear the hard X-ray variability (Madejski et al. 2000). A small, dense inner disk is also required to produce the observed maser emission, so we identify the extreme absorber with the maser disk. This material is distributed over a patch \( \sim 0.7 \times 0.1 \text{ pc}^2 \) in size (Greenhill et al. 1997), representing H\( \alpha \) densities on the order of \( 10^{8}–10^{10} \text{ cm}^{-3} \) for fractional H\( \alpha \)O abundances of \( 10^{-4} \) to \( 10^{-3} \) (Elitzur 1992), so giving a potential column of \( N_{\text{H}} > 10^{26} \text{ cm}^{-2} \). Since this is considerably bigger than the observed obscuration, we may not be in the maxi-

In addition to the dense absorbing disk, the central engine
must be completely embedded in obscuring material within
\( \sim 25 \text{ pc} \) so that UV and soft X-ray fluxes do not escape (Marconi et al. 2000). Although this additional absorption
could be associated with material from the starburst-related inflow along a bar (Ott et al. 2001), we suggest that it may be a high-latitude extension of the dense absorber (i.e., the maser-emitting material is a thickening in the equatorial plane). As such, the central parsec of NGC 4945 could be more gas rich than that of most other Seyfert galaxies. In this sense, NGC 4945 may be similar to NGC 3079, another active galaxy that exhibits very large columns (Iyomoto et al. 2001), substantial nuclear star formation (Cecil et al. 2001 and references therein), and a disordered but otherwise disklike distribution of H₂O masers (Trotter et al. 1998). This absorber is probably seen in the column of \( N_\text{H} \sim 7 \times 10^{22} \text{cm}^{-2} \) inferred on the reflected nuclear X-ray spectrum, corresponding to \( \mathcal{A} \sim 35 \). This is also the absorbing column seen to the far-IR nuclear source (Krabbe et al. 2001).

On much larger scales there is absorption associated with the dusty nuclear starburst ring, which forms a \( \sim 100–200 \text{pc} \) torus around the nucleus (Marconi et al. 2000). This picture fits into the growing evidence for two distinct absorption structures in many AGNs, with a compact, extreme absorption region surrounded by an extended dusty lower absorption region (e.g., Granato, Danese, & Franceschini 1997).

The energy from supernovae in the starburst ring produces hot multiphase gas, which emits in the soft X-ray range. A population of X-ray binaries may also contribute to the spectrum from this region, which would remove the requirement for some of this gas to be as hot as \( \sim 6 \text{keV} \). However, flux at \( \sim 3–4 \text{keV} \) is also required in the superwind (diff-2) region, where it is hard to envisage anything other than hot gas being present. This intrinsic diffuse emission is augmented by some scattering of the absorbed nuclear flux in cold, optically thick material. These cool clumps most probably represent star-forming cores, as these have density \( n \sim 10^6 \text{cm}^{-3} \) and size scales of 1 pc (Plume et al. 1997).

6. CONCLUSIONS

The unsurpassed X-ray imaging ability of the Chandra satellite allows us to disentangle the AGN and starburst/superwind contributions in NGC 4945. Chandra sees the nucleus only in reflection; simultaneous RXTE data show the direct nuclear flux absorbed by an extreme column of \( \sim 4 \times 10^{24} \text{cm}^{-2} \).

The starburst/superwind gas is clearly multiphase, with cool clumps (seen in reflection and iron fluorescence line emission at 6.4 keV) coexisting with hot gas. The hot gas is itself clumped rather than uniform, as otherwise it would be strongly photoionized, in conflict with the observed spectrum from the furthest region (diff-2). We show that the self-consistent scattered emission from the hot gas is probably unimportant compared to its diffuse emission.

The extreme absorption of \( N_\text{H} > 10^{24} \text{cm}^{-2} \) seen toward the nucleus cannot completely cover the source in all directions, as the extended 6.4 keV fluorescence line emission clearly shows that the hard X-rays (7–10 keV) from the AGN illuminate the starburst ring. However, the lack of optical/IR high-excitation lines from this region equally clearly shows that the UV/soft X-rays from the AGN do not illuminate this material. Either the AGN does not produce UV/soft X-rays (which seems highly unlikely) or they are absorbed in all directions which requires columns of \( N_\text{H} > 10^{21–22} \text{cm}^{-2} \). This implies that the nucleus is completely embedded in a column of \( \sim 10^{22–23} \text{cm}^{-2} \), probably associated with molecular gas driven into the nucleus by the starburst/superwind.

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