THE HIGHEST RESOLUTION CHANDRA VIEW OF PHOTOIONIZATION AND JET-CLOUD INTERACTION IN THE NUCLEAR REGION OF NGC 4151

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Received 2009 July 31; accepted 2009 September 8; published 2009 September 30

ABSTRACT

We report high resolution imaging of the nucleus of the Seyfert 1 galaxy NGC 4151 obtained with a 50 ks Chandra High Resolution Camera (HRC) observation. The HRC image resolves the emission on spatial scales of 0.5, ~30 pc, showing an extended X-ray morphology overall consistent with the narrow-line region (NLR) seen in optical line emission. Removal of the bright point-like nuclear source and image deconvolution techniques both reveal X-ray enhancements that closely match the substructures seen in the Hubble Space Telescope [O iii] image and prominent knots in the radio jet. We find that most of the NLR clouds in NGC 4151 have [O iii]/soft X-ray ratio ~10, despite the distance of the clouds from the nucleus. This ratio is consistent with the values observed in NLRs of some Seyfert 2 galaxies, which indicates a uniform ionization parameter even at large radii and a density decreasing as r^{-2} as expected for a nuclear wind scenario. The [O iii]/X-ray ratios at the location of radio knots show an excess of X-ray emission, suggesting shock heating in addition to photoionization. We examine various mechanisms for the X-ray emission and find that, in contrast to jet-related X-ray emission in more powerful active galactic nucleus, the observed jet parameters in NGC 4151 are inconsistent with synchrotron emission, synchrotron self-Compton, inverse Compton of cosmic microwave background photons or galaxy optical light. Instead, our results favor thermal emission from the interaction between radio outflow and NLR gas clouds as the origin for the X-ray emission associated with the jet. This supports previous claims that frequent jet–interstellar medium interaction may explain why jets in Seyfert galaxies appear small, slow, and thermally dominated, distinct from those kpc-scale jets in the radio galaxies.

Key words: galaxies: individual (NGC 4151) – galaxies: jets – galaxies: Seyfert – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

X-ray counterparts to the powerful radio jets that extend beyond kpc, or even Mpc, and at a distance from radio-loud active galactic nuclei (AGNs) are well studied (e.g., M87, Cen A, and 3C273; see Harris & Krawczynski 2006 for a review). However, their weaker analogs, the smaller jets found on the scales of the narrow-line region (NLR) in many radio-quiet Seyfert galaxies (Nagar et al. 1999; Terashima & Wilson 2003; Ulvestad 2003 and references therein) are less well studied in the X-rays. The limiting reasons are the angular resolution achievable in X-rays, even with the Chandra X-ray Observatory, and the complex circumnuclear environment often including X-ray emission contributed from starburst and the ionized gas in the NLR (e.g., Wilson et al. 1992; Young et al. 2001; Wilson & Yang 2002; Wang et al. 2009).

Although challenging, studying these jets and the emission-line gas with high resolution imaging provides a valuable probe of the interstellar medium (ISM) fueling the central engine and the interaction between the AGN and the host galaxy (e.g., Bianchi et al. 2006). In particular, such high resolution data allow the investigation of the importance of AGN jets in the energetics and kinematics of the NLR in addition to the direct ultraviolet (UV) emission from the nucleus.

An ideal object for such a study is NGC 4151 (D ~ 13.3 Mpc; Mundell et al. 1999). It is often considered as the nearest archetypal Seyfert 1 galaxy (see Ulrich 2000 for a review), and the nucleus contains a linear radio jet ~3.5 (230 pc; Wilson & Ulvestad 1982; Carral et al. 1990; Pedlar et al. 1993; Mundell et al. 1995). The biconical NLR and the extended NLR (ENLR) are elongated up to ~10^\prime\prime along the northeast (NE) and southwest (SW) of the nucleus and not aligned with the radio jet (Mundell et al. 2003). The ionized gas appears clumpy in high resolution Hubble Space Telescope (HST) images (e.g., Boksenberg et al. 1995; Winge et al. 1997; Kaiser et al. 2000). Previous Chandra ACIS images show extended X-ray emission that is well correlated with the optical forbidden line emission at r > 1.5′ (e.g., Ogle et al. 2000; Yang et al. 2001), but cannot investigate the association between X-ray emission and the radio jet due to pile-up and resolution.

In this paper, we present the first Chandra High Resolution Camera (HRC) observation of the NGC 4151 nucleus. The smaller pixel size of HRC microchannel plate (0′.13 pixel^{-1}; Chandra Proposers’ Observatory Guide) allows good sampling of the Chandra High Resolution Mirror Assembly (HRMA; van Speybroeck et al. 1997; Weisskopf et al. 2002) point-spread function (PSF; FWHM~0′.4), which is instead undersampled by the ACIS detector because of the larger physical size of CCD pixel (0′.49 pixel^{-1}). Lack of pile-up, the superior spatial resolution of the HRC data allows us to examine the X-ray morphology of the nuclear region, and identify enhancements in the X-ray image with features seen in other wave bands.

2. OBSERVATIONS AND DATA REDUCTION

NGC 4151 was observed on 2008 March 2 starting at 10:19:48 (UT) with the Chandra HRC-I for 50.18 ks. The nominal pointing was (α = 12h10m31.8s, δ = 39°24′33″), which places the optical nucleus of the galaxy (α = 12h10m32.6s, δ = 39°24′21″; Clements 1981) on axis. The total region covered was 30′ × 30′.3

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3 http://cxc.harvard.edu/proposer/POG/.
Figure 1. (a) ∼8' × 8' HRC image of the circumnuclear region of NGC 4151. Contours of [O iii] λ5007 line emission are overlaid. (b) Simulated HRC PSF image. Comparing (a) and (b), the nuclear region of NGC 4151 clearly shows extended emission besides the central bright point-like source.

The HRC data were reprocessed with Chandra Interactive Analysis of Observations (CIAO) tool hrc_process_events using the CIAO software package version 4.1 and Chandra Calibration Database (CALDB) version 4.1.2 to generate new level 2 file that has the latest calibration applied and the amplifier ringing effect removed. The total exposure time was 49.67 ks after filtering of good time intervals.

To improve the accuracy of astrometry, X-ray source detection was performed on the HRC image using the wavdetect algorithm (Freeman et al. 2002) and the positions of X-ray point sources were compared to the coordinates from the USNO-B1.0 Catalog (Monet et al. 2003), yielding excellent absolute astrometric accuracy of 0.2\′′ (1σ).

3. IMAGE ANALYSIS AND RESULTS

3.1. X-ray Morphology

Figure 1(a) presents the HRC-I image of the NGC 4151 nuclear region, showing the central 8'' × 8'' region. The X-ray emission in the nuclear region is resolved into distinct components in the HRC image, namely a bright point-like, unresolved nucleus and resolved extended regions toward NE along position angle (P.A.) ∼ 48° and SW along P.A. ∼ 233°. The curved X-ray emission 3'' SW of the nucleus shows distinct segments in the HRC, which closely follows the [O iii] λ5007 emission (e.g., HST/WFPC2 F502N image; Kaiser et al. 2000). Although the ACIS and HETG zeroth-order images show similar elongation and hints of structure, some features seen in the HRC image were not discernible due to the larger ACIS pixel size (cf. Figure 1 in Yang et al. 2001). Results on new deep ACIS imaging and detailed spectral study focusing on X-ray emission associated with the ENLR will be presented in a separate paper (J. Wang et al. 2009, in preparation).

3.2. Preliminary Extent Analysis

In order to look for low brightness emission around the bright nucleus, we performed PSF subtraction at the nucleus position. The Chandra PSF was simulated with the Chandra Ray Tracer (ChaRT) using a monochromatic energy at 1 keV, sufficient for HRC data (see ChaRT thread noted above). The rays were then projected onto the HRC detector with CIAO tool psf_project_ray adopting a 0.2 Gaussian blurring, which gives a PSF that has a sharper radial profile matching the inner 0.5 data well and will be used to perform the PSF subtraction later. Figures 1(a) and (b) compare the source image and the PSF image.

In Figure 2, we illustrate the presence of extended emission along NE–SW direction by comparing surface brightness profiles. The nucleus radial profile deviates above the simulated PSF profile at r ∼ 3 pixels (0.4), indicating the presence of extended emission. In contrast, the radial profile extracted from two sectors perpendicular to the extended emission (between P.A. ∼ 290° and 20°, and between P.A. ∼ 110° and 200°), which accurately follows the simulated PSF profile.
From the HRC count rate, we estimate the absorption corrected 0.5–10 keV flux $F_{X,\text{nuc}} = 1.1 \times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$ ($L_{X,\text{nuc}} = 2.3 \times 10^{42}$ erg s$^{-1}$) and $F_{X,\text{ext}} = 4.3 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ ($L_{X,\text{ext}} = 9 \times 10^{39}$ erg s$^{-1}$) with PIMMS, assuming a power-law spectrum ($\Gamma = 1.65$, $N_H = 3 \times 10^{22}$ cm$^{-2}$; Schuch & Warwick 2002) and a thermal bremsstrahlung spectrum ($kT = 0.57$ keV, $N_H = 2 \times 10^{20}$ cm$^{-2}$; Yang et al. 2001) for the nuclear point source and the extended emission (within a 4′′ radius of the nucleus), respectively. Note that although these flux values agree with previous measurements in the literature (e.g., Weaver et al. 1994; Yang et al. 2001), they rely on the assumed spectral models and should be treated as estimates. For example, varying the $kT$ from 0.3 keV to 1 keV results in a ±40% deviation from the current flux. Adopting the Raymond–Smith thermal plasma model for the same $kT = 0.57$ keV will increase the flux to $4.9 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ due to the presence of strong emission lines.

3.3. Image with PSF Subtraction

The peak of the PSF image is centered at the observed brightness peak of the point-like source at detector position (DETX, DETY) = (16320, 16289), and its peak intensity is renormalized to match the point-like source. The resulting PSF-subtracted HRC image in the central ∼8′′ × 8′′ region is shown in Figure 3 and will be compared with the images restored with deconvolution algorithms in Section 4. To check how misalignments between source image and PSF image may affect the subtraction, we offset the PSF image ±1 pixel around the observed brightness peak of the point-like source at detector position and reid the subtraction. There are significant asymmetries (point source residuals) in all these offset PSF-subtracted images with over-subtraction toward the shifted direction and bright residual in the opposite direction, indicating that the subtraction is off-center and our initial choice is justified.

4. DISCUSSION

The PSF-subtracted image and deconvolved images show similar X-ray structures, clearly indicating some relation to the NLR gas, the radio jet, and the interaction of the jet with the ISM. Overall, there is a good correlation between enhancements in [O iii] and X-ray emission (Figures 3 and 4), possibly because both originate from the same photoionized gas. In the following sections, we investigate how the X-ray emission is associated with the NLR clouds and with the bright knots in the radio jet.

4.1. Constraints on the X-ray Emission from the [O iii] Clouds

Bianchi et al. (2006) surveyed the NLRs of eight nearby Seyfert 2 galaxies with HST and Chandra, and found kpc-scale soft X-ray emission coincident with the extent and morphology of the [O iii] emission. They suggested that the same gas photoionized by the AGN continuum can simultaneously produce the X-ray and [O iii] emission with the observed ratios. Note that these ratios were the average values over ≈kpc regions as the ACIS images did not allow comparisons of the X-ray emission with the small clumps seen in HST images.

For NGC 4151, the unprecedented high spatial resolution HRC image enables us to compare the substructures of the X-ray emission and those of the NLR clouds. Figure 5 compares the details of a 5′′ × 5′′ HST Faint Object Camera (FOC) f/96 [O iii]5007 image of the nuclear region (Winge et al. 1997) with the restored HRC image using EMC2 deconvolution. Note the striking correspondence of the optical [O iii] substructures to the X-ray morphology, especially the faint cloud to the NE and a curved extension to the SW. The main cloud features are labeled. Using the calibrated FOC image, we measured the [O iii] fluxes for the clouds following the FOC Data Handbook, and listed them in Table 1. Figure 5 also shows the Very Long Baseline Army (VLBA) radio image contoured on the FOC image and

7 http://www.stsci.edu/hst/foc/documents/foc_handbook.html.
Figure 4. HRC image of the nuclear region after (a) Richardson–Lucy deconvolution and (b) EMC2 deconvolution. Contours of HST/FOC F502N \([\text{O} \text{iii}]\) line emission (Winge et al. 1997) are overlaid.

(A color version of this figure is available in the online journal.)

Figure 5. (a) HST/FOC \([\text{O} \text{iii}]\) image of the nuclear region (Winge et al. 1997). The clouds listed in Table 1 are labeled. (b) Restored HRC image using EMC2 deconvolution with contours of \([\text{O} \text{iii}]\) line emission from (a) is overlaid. (c) and (d) show the VLBA+VLA \(\lambda 21\) cm continuum contours (Mundell et al. 2003) overlaid on the HST/FOC \([\text{O} \text{iii}]\) image and the HRC image with EMC2 deconvolution, respectively.

(A color version of this figure is available in the online journal.)
the HRC image with EMC2 deconvolution, outlining the plasma flow of the spine of the jet and the X-ray emission with respect to the jet. We will discuss the radio–X-ray correspondence in Section 4.2 and the overall radio, [O iii], and X-ray comparison in Section 4.3.

To compare with results in Bianchi et al. (2006), the 0.5–2 keV X-ray fluxes were also derived using counts extracted from the same regions, with the deconvolved HRC image and PIMMS. To check the levels of ionization in different clouds, in Figure 6 we show the [O iii]/soft X-ray ratio for the distinct cloud features (Table 1) at various radii to the nucleus (∼25 pc–150 pc).

We note that two clouds (no. 5 and no. 6) show much higher [O iii]/X-ray ratio (∼100) than the typical value, implying lower ionization at these locations. Both clouds lie along the outermost edge of the SW cone (Figure 5; see also Figure 9). Comparing to other clouds at the same radii (e.g., no. 3), their lower ionization could be explained by either a lower incident ionizing flux because of more screening at these locations from absorbers covering the nuclear source (see Kraemer et al., 2008), or higher density in these clouds as they are swept up by the outflow. It has been suggested that the NLR could consist of different components with various degree of ionization (e.g., Kinkhabwala et al. 2002).

In addition, the [O iii]/X-ray ratios at the four jet knot locations (C1, C2, C3, and C5; see Section 4.2 and Figure 7) were measured, and found to be uniformly low, ∼2. Only one cloud (no. 9) has a similar low ratio of 3. This implies higher X-ray emission compared to the other clouds under photoionization. The enhanced X-ray emission is likely associated with the outflowing radio plasma, as many radio jets have X-ray counterparts originating from non-thermal and thermal processes (Harris & Krawczynski 2006). We explore the origin of the X-ray emission associated with these knots in the next section.

To explain the X-ray and [O iii] ratio in a single photoionized medium, Bianchi et al. (2006) generated a photoionization model with CLOUDY (version 96.01, last described by Ferland et al. 1998). We also plot the model predicted curves in Figure 6 for different radial density profiles, where the electron density was assumed to have a power-law radial dependence \( n_e \propto r^{-\beta} \) (\( \beta = 0 \) is constant density, and \( \beta = -2 \) represents a freely expanding wind).

We find that the eight remaining NLR clouds in NGC 4151 have [O iii]/X-ray (0.5–2 keV) ratio close to 10, despite the distance of the clouds from the nucleus. This ratio is consistent with the range of ∼3–11 in the Seyfert galaxies observed by Bianchi et al. (2006), although it is at the higher end. The fairly constant [O iii]/X-ray ratios indicate an almost uniform ionization parameter even at large radii, requiring a density dependence close to \( r^{-2} \) as expected for a wind from the nucleus (e.g., Krolik & Kriss 1995; Elvis 2000). This agrees with the conclusion in Bianchi et al. (2006) and the results found for some well-studied NLRs (e.g., Kraemer & Crenshaw 2000; Collins et al. 2005; Kraemer et al. 2008).

### 4.2. Constraints on the X-ray Emission from the Radio Jet Knots

Figure 7 shows the inner ∼4′′ × 4′′ region of the PSF-subtracted image and the restored image using EMC2 deconvolution, overlaid with contours of the radio jet (MERLIN 1.4 GHz...
map; Mundell et al. 1995). There are five main radio components in the radio jet (C1–C5) from a number of studies (Carral et al. 1990; Pedlar et al. 1993; Mundell et al. 1995). C4 is known as the position of the nucleus and was used to align the X-ray peak. In jet components C3 and C5, the radio knot and X-ray enhancement appear to originate in the same volume at current resolution of the X-ray image. On the other hand, C2 has little X-ray emission but is straddled by two X-ray blobs and coincides with jet deflections in “Z”-like shape (see Figure 7 and also Figure 5).

To understand the association of X-ray emission with the jet knots, we consider the following emission mechanisms in the general framework of X-ray emission processes in radio jets (Harris & Krawczynski 2006). The spectral index of a power law $\alpha$ is defined by flux density, $S_{\nu} \propto \nu^{-\alpha}$, following the radio convention. To evaluate the X-ray flux densities of the knots, we extracted HRC counts from the EMC2 deconvolved image using regions defined by radio contour (3σ at 1 mJy), which have comparable resolution (~0′′15; Mundell et al. 1995). We also attempted to extract HRC counts from the PSF-subtracted image using regions defined by resampling radio contours to match the lower HRC resolution, which yielded similar counts (excluding the nucleus, C4). The HRC has poor energy resolution and the data are not amenable to standard spectral fitting; therefore, the X-ray flux is estimated over 0.1–10 keV range with PIMMS (see Table 2 notes for details) assuming a power-law index $-\alpha = 1.0$, a typical value in low power radio jets (Harris & Krawczynski 2006) and Galactic-only absorption ($N_H = 2 \times 10^{20} \text{cm}^{-2}$; Yang et al. 2001). Radio flux densities of the knots were taken from Pedlar et al. (1993).

### Synchrotron Emission

In many radio jets, circumstantial evidence exists for the synchrotron process generating the X-rays in the knots. If this is the dominant process in the NGC 4151 jet, the X-ray intensity would be consistent with a single power-law extrapolation or a broken power-law concaving downward. Table 2 gives the emission parameters of the radio components. Following the minimum energy argument (or equipartition) generally adopted for synchrotron sources (e.g., Govoni & Feretti 2004), we listed in Table 3 the typical magnetic fields in the knots, most of which have $B \approx 1 \text{ mG}$, assuming a proton-to-electron ratio $K = 100$ (Pedlar et al. 1993). Figure 8 shows spectra of the radio knots. The observed X-ray intensities lie orders of magnitude above the extension of the radio synchrotron spectra. This cannot be attributed to the uncertainties in the radio or X-ray flux density measurements, which indicate that a simple synchrotron model is insufficient for the X-ray emission.
Inverse Compton Emission. Low frequency photons are scattered by relativistic electrons to higher frequency through the inverse Compton (IC) process. One common emission process in radio jets is the synchrotron self-Compton (SSC) emission. The photon energy density from the synchrotron spectrum in each knot can be calculated using \( u_{\text{sync}} = 3L_{\text{sync}} R / 4 c V \) (Wilson et al. 2000) and assuming uniformly emitting spheres to derive volumes, where \( L_{\text{sync}} \) is the radio luminosity, \( R \) is the sphere radius, \( c \) is the speed of light, and \( V \) is the volume. Another common IC process in radio jets is the IC scattering of the cosmic microwave background (CMB), which has the photon energy density \( u_{\text{CMB}} = 4 \times 10^{-13} \text{ ergs cm}^{-3} \).

Both \( u_{\text{sync}} \) and \( u_{\text{CMB}} \) are much lower than photon energy density of the combined AGN and star light in the NGC 4151 nuclear region, therefore considering the latter as the dominant seed photons is more appropriate. To simplify the estimate, we approximate the photon field as blackbody radiation peaking at \( T = 4000 \text{ K} \), with a energy density \( u_{\text{ph}} = 2 \text{ ergs cm}^{-3} \). Following Blumenthal & Gould (1970), we derive an estimate of the magnetic field from the ratio between the X-ray and the radio fluxes. For all the cases, the required \( B \) values for IC mechanism to explain the X-ray emission are \( \sim 3 \) orders of magnitude larger than the equipartition magnetic field \( B \sim 1 \text{ mG} \), which is unlikely.

To ease the requirement on the magnetic field, beaming model with relativistic bulk jet velocity must be invoked to boost IC emission. However, there is strong evidence against a highly relativistic bulk velocity of NGC 4151 jet. First, the angle between the jet and our line of sight is \( \sim 40^\circ \) (Pedlar et al. 1993). The knots that have similar distance to the nucleus (C2 and C5) also have comparable X-ray/radio intensities. The fact that we see a two-sided, non-boosted radio jet suggests the bulk velocity is not highly relativistic. Secondly, Ulvestad et al. (2005) measured the speeds of the jet component with VLBI and found 0.05c and 0.028c at 0.16 and 6.8 pc from the nucleus, respectively, confirming the non-relativistic jet motions. None of the forms of IC emission can account for the observed X-ray fluxes.

**Thermal Bremsstrahlung Emission.** The X-ray emission from the radio features may originate from hot gas rather than from non-thermal mechanism, although with the current resolution we cannot distinguish if the hot gas is located within the radio emitting volume or around the jet. Considering the morphology, jet–cloud interaction seems to be present. We adopted a \( kT \sim 0.6 \text{ keV} \) for the thermal model as a low \( kT \) is typical of the X-ray emission from the NLR ionized gas and measured from the X-ray spectral fitting (Yang et al. 2001). In Table 3, we calculated the emission measure, electron number density, and thermal pressure for each knot. It is often argued that the absence of Faraday rotation and depolarization places a limit on the required electron densities (e.g., de Young 2002). In NGC 4151, we derive \( n_e < 10^{11} \text{ cm}^{-3} \) from optical polarization measurement of Kruszelewski (1971), assuming an equipartition field \( B \sim 10^{-3} \text{G} \). The \( n_e \) required for thermal emission is orders of magnitude smaller than this limit. A thermal origin is thus highly plausible.

4.3. X-ray, Radio, and [O iii] Comparison

Figure 9 altogether compares X-ray emission (red) with the radio jet (blue; MERLIN 1.4 GHz map; Mundell et al. 1995) and optical NLR emission (green; HST/FOC F502N [O iii]λ5007 image; Winge et al. 1997) in projection. The radio component C4 contains the AGN (see higher resolution VLBA studies by Ulvestad et al. 2005; Mundell et al. 2003). Assuming that the peak of the optical nuclear emission originates from the AGN, we aligned the X-ray, optical, and radio nuclei.

There are X-ray enhancements associated with the bright radio knots in the jet as well as the NLR clouds (see also Figure 7). The overall morphology in the three bands is consistent with the scenario that clumpy material lies in the path of the jet and is shock-heated to X-ray emitting temperature from the impact with the outflowing radio plasma from the nucleus. C1 has largely diffuse morphology in the radio and the weak X-ray emission; it is mostly in a [O iii] emission cloud free region. Around knots C2 and C5, as noted in Mundell et al. (2003), a number of [O iii] clouds are closely associated with the radio knots and appear to bound the radio knots (see Figure 5(c)). The morphologically disturbed radio jet may have cleared a path through the NLR (Mundell et al. 2003).
Some evidence has been reported supporting this jet–cloud interaction scenario. Kinematic studies mapping the full velocity field of the NLR clouds (Winge et al. 1999; Kaiser et al. 2000) found that the jet may be influential in producing the high velocity dispersions for the clouds in the inner 4", although not directly responsible for the acceleration of the gas (Crenshaw et al. 2000; Das et al. 2005). Mundell et al. (2003) examined the apparent radio correspondence with these clouds, suggesting that sites of radio jet deflection are aligned in projection with high velocity dispersion clouds.

Storchi-Bergmann et al. (2009) mapped near infrared emission-line intensities and ratios in the NLR of NGC 4151, which probe the effects of shocks produced by the jet on the NLR gas. We note that there are enhancements of the [Fe ii] emission at the locations of radio knots C2 and C5 in these IR maps (e.g., the [Fe ii]/Paβ), consistent with being the spots of jet–cloud interaction. As a minimal requirement of the shock scenario following Kraft et al. (2009), the pressure of the clouds must be less than the ram pressure of the jet, which translates to \( p_{\text{knot}} < 2 P_{\text{jet}}/v_j A \), where \( p_{\text{knot}} \) is the pressure of a knot, \( P_{\text{jet}} \) is the jet power, \( A \) is the cross section area, and \( v_j \) is the jet velocity. Using an estimated jet power \( P_{\text{jet}} \approx 1.6 \times 10^{43} \) ergs s\(^{-1}\) (Allen et al. 2006), \( v_j = 0.028c \) (Ulvestad et al. 2005), and \( A = 30 \) pc, we find \( p_{\text{knot}} < 10^{-6} \) dyne cm\(^{-2}\), which is satisfied by our derived pressure (Table 3).

Our estimates for the NGC 4151 jet assuming thermal origin of the X-ray emission match well with the characteristics of the jets in hydrodynamic simulations (e.g., Rossi et al. 2000; Saxton et al. 2005), which are relatively heavy (\( \rho > 1 \) cm\(^{-3}\)) and slow (\( v < 5 \times 10^4 \) km s\(^{-1}\)). This is also consistent with the conclusion of the studies of a jet-dominated Seyfert Mkn 78 (Whittle & Wilson 2004; Whittle et al. 2005), where a thermally dominated, slow, and dense Seyfert jet encountering dense gas clouds was identified.

Such jet–cloud interaction may explain why the jets in Seyfert galaxies seem very different from those in radio-loud AGNs (Middelberg et al. 2007): they are not able to propagate freely as do the well-collimated, galactic scale jets in radio galaxies. Besides NGC 4151, there is strong evidence for interactions of radio jets with the ISM on the scales of NLRs in Seyfert galaxies (e.g., NGC 1068, Wilson & Ulvestad 1982; IC 5063, Oosterloo et al. 2000; NGC 2110, Evans et al. 2006; III Zw 2, Brunthaler et al. 2005; and NGC 3079, Middelberg et al. 2007), which would be worth Chandra follow-up imaging to locate the X-ray emission.

It is also worth noting that the NE part of the X-ray emission (e.g., cloud no. 9) appears brighter than the SW part. According to the modeled geometry of the bicone of ionized gas and host galaxy in Das et al. (2005), the SW side is closer to us and our line of sight is outside of the bicone. One plausible explanation for the enhanced X-ray emission in NE is that, the NE bicone intersects with the NE galactic disk and the X-ray emitting medium there may have higher density. On the other hand, although SW part of the bicone also intersects the disk, our line of sight to the intersection goes through the cone and may be subject to higher absorption (see Figure 10 in Evans et al. 1993).

As a cautionary note, physical association between the features seen in different bands along the line of sight is not warranted because of the projection effect. At the knot position, at least part of the X-ray emission could be contributed from the NLR clouds directly ionized by the AGN (e.g., Bianchi et al. 2006). But as we showed in Section 4.1, C1, C2, and C5 are not associated with any bright NLR clouds. Instead, thermal X-ray emission is expected in the jet–ISM interaction scenario described above, which is well supported by the low [O iii]/soft-X ratios and the enhancement of [Fe ii], together with the multiwavelength morphologies.

### 5. CONCLUSIONS

The high resolution imaging of the NGC 4151 nucleus obtained with Chandra HRC shows X-ray morphology that is both overall consistent with the NLR seen in optical line emission, with substructures closely matching the [O iii] clouds, and with knots in the radio jet, implying X-ray emission associated with both the photoionized gas and the jet components.

We find that most of the NLR clouds in NGC 4151 have [O iii]/soft X-ray ratio \( \sim 10 \), at or a factor of \( \sim 10 \) in distance of the clouds from the nucleus. The radially constant ratio indicates a uniform ionization parameters even at large radii and a density dependence \( \propto r^{-2} \) as expected for a nuclear wind.

The calculations of required jet parameters from observed X-ray and radio properties do not favor synchrotron emission, SSC emission, or IC of CMB photons and the local galaxy light. Thermal emission from interaction between radio outflow and the NLR clouds is the most favorable explanation.

Future high spatial resolution X-ray observatories, such as Generation-X with an angular resolution of \( 0.1' \) (Brissenden 2009), will be able to unambiguously resolve the X-ray emission from the knots and the NLR with high spectral resolution and so gain important new knowledge of the outflows of both thermal and non-thermal plasma from Seyfert galaxies.

We thank the anonymous referee for useful comments that improved the clarity of our paper. This work is partially supported by NASA grant GO8-9101X and NASA contract NAS8-39073 (CXC). We are grateful to Dan Harris and Aneta Siemiginowska for their stimulating discussion on radio jets. J.W. thanks E. Galle and M. Juda (CXC) for technical assistance in HRC data reduction.

Facility: CXO (HRC, ACIS)

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