A SMALL X-RAY CORONA OF THE NARROW-ANGLE TAIL RADIO GALAXY NGC 1265 SOARING THROUGH THE PERSEUS CLUSTER

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ABSTRACT

A deep Chandra observation of NGC 1265 (3C 83.1B), the prototype for the narrow-angle tail (NAT) radio galaxy, reveals a small cool X-ray thermal corona (∼0.6 keV) embedded in the hot ICM of the Perseus cluster (∼6.7 keV). The corona is asymmetric with a sharp edge (∼222, or 0.8 kpc from the nucleus) to the south and an extension to the north (at least ∼8′′ from the nucleus), which are interpreted as the result of ram pressure, as it cannot be explained solely by the static ICM confinement. We estimate that the corona is moving with a velocity of ∼2.4–4.2 times the local sound speed to the south. The presence of the sharp edge on this small corona indicates that the transport processes are largely suppressed by the magnetic field there. The magnetic field around the corona also suppresses heat conduction by at least a factor of ∼60 across the corona boundary. We conclude that it is unrealistic to study the interaction between the small X-ray coronae and the hot ICM without considering the roles played by the magnetic field, a factor not included in current simulations. An absorbed (N_H = 1.5–3 × 10^{22} cm^{-2}) nucleus is also detected, which is not usual for FR I radio galaxies. Weak X-ray emission from three inner radio knots in the jets is also detected. Indentations at the east and west of the corona indicate interaction between the jets and the X-ray corona. Narrow jets carry great amounts of energy out of the central AGN and release the energy outside the corona, preserving the tiny and vulnerable corona. This case reveals that the inner kiloparsec core of the corona of massive galaxies can survive both high-speed stripping and powerful AGN feedback. Thus, the cooling of the X-ray coronae potentially provides fuel to the central SMBH in rich environments in which the amount of galactic cold gas is at a minimum.

Subject headings: galaxies: clusters: general — galaxies: clusters: individual (Perseus) — galaxies: individual (NGC 1265) — galaxies: jets — magnetic fields — radio continuum: galaxies — X-rays: galaxies

1. INTRODUCTION

Chandra observations have discovered eight small but spatially resolved thermal coronae of early-type galaxies in hot cluster (kT_{ICM} > 3 keV) environments (Vikhlinin et al. 2001; Yamasaki et al. 2002; Sun et al. 2005, hereafter S05). As summarized in S05, the coronae of massive galaxies can survive in spite of evaporation and gas stripping by the hot and dense intracluster medium (ICM), as well as by the energy imparted by the central AGN outbursts. Thus, the properties of these “survivors” can put constraints on important physics, e.g., microscopic transport processes, gas stripping, stellar mass injection, and active galactic nucleus (AGN) heating (e.g., Vikhlinin et al. 2001; S05). The presence of a dense gas component (M_{gas} \sim 10^{7} M_{\odot} with a high central density of 0.1–0.3 cm^{-3}) potentially provides the fuel for the central supermassive black hole (SMBH) in environments in which the amount of the galactic cold gas is at a minimum. Moreover, the survivor properties shed light on the evolution history of their hosts.

For galaxy coronae previously discovered in rich clusters, there has been no strong evidence that the host galaxy is moving at a high velocity relative to the surrounding ICM or for strong nuclear activity in the host galaxy. In this paper, we show an extreme example, in which the galaxy is known to be moving very fast (>2500 km s^{-1}) through a hot cluster and to host a powerful AGN with strong radio emission. NGC 1265 (3C 83.1B, 4C 41.06) is the prototype of narrow-angle tail (NAT) radio sources (Ryle & Windram 1968). NGC 1265 is in the Perseus cluster, 27′′ northwest of the cluster center (Fig. 1). Its radial velocity (7536 km s^{-1}; Huchra et al. 1999) is \sim 2300 km s^{-1} higher than that of the Perseus cD galaxy NGC 1275 (5264 km s^{-1}; Huchra et al. 1999), indicating a large infalling velocity for NGC 1265. Highly complicated radio morphologies are revealed from 2 to 92 cm (O’Dea & Owen 1986; Sijbring & de Bruyn 1998). Two narrow east-west radio jets emerge from the nucleus but are quickly bent toward the north to form two tails, which are further merged 4′ north of the nucleus. Radio images at 49 and 92 cm (Sijbring & de Bruyn 1998) further reveal a low surface brightness extension of the tail that bends at least three times over an angle of almost 360°. The projected total length of the tail is at least 40′ (or 0.88 Mpc). This complex morphology was tentatively explained as the result of the galaxy’s infalling orbit and the bulk flow of the ICM gas to the east (Sijbring & de Bruyn 1998). Despite the unique appearance of the galaxy in the radio, optically it is a rather normal elliptical. A small dust lane is revealed by the Hubble Space Telescope (HST) image (Fig. 1), which is almost perpendicular to the jet, direction and aligned with the galaxy major axis. The galaxy is not a strong X-ray emitter according to the ROSAT data (Rhee et al. 1994). We obtained a deep (94 ks) Chandra observation on this galaxy in which the X-ray source is fully resolved.

The velocity of the Perseus cluster is 5366 km s^{-1} (Struble & Rood 1999). We use a redshift of 0.018 to calculate the luminosity distance of NGC 1265, assuming H_0 = 70 km s^{-1} Mpc^{-1}, \Omega_M = 0.3, and \Omega_{\Lambda} = 0.7. The luminosity distance is 78.4 Mpc, and 1′′ corresponds to 0.366 kpc. We use the Galactic absorption of 1.46 × 10^{21} cm^{-2}, which is consistent with the absorption column derived from the X-ray analysis. The solar photospheric abundance table by Anders & Grevesse (1989) is used in the spectral fits. Uncertainties quoted are 1 \sigma.
2. CHANDRA OBSERVATION

2.1. Chandra Data Reduction

A 93.9 ks Chandra observation was performed with the Advanced CCD Imaging Spectrometer (ACIS) on 2003 March 15–16. The optical axis lies on CCD S3, and the data were telemetered in very faint mode. Standard data analysis is performed, which includes the correction for the slow gain change. Since CCD S1 is off, we investigated the background light curve from the source-free region on CCD S3. Excluding time intervals with significant background flares results in a total exposure of 65.7 ks. Although the cluster emission is still significant across the whole Chandra field, our analysis is not affected by any weak background flares on small scales, since a local background is used. For the analysis of the cluster diffuse emission, we used the period D background file, aciss_D_7_bg_evt_271103.fits. The particle background level (measured in PHA channels 2500–3000 ADU) was 1.1% higher than that of the period D background data. Thus, we increased the background normalization by 1.1%.

We corrected for the ACIS low-energy quantum efficiency (QE) degradation, which increases with time and is positionally dependent. The calibration files used correspond to Chandra Calibration Database 3.0.0 from the Chandra X-ray Center. In the spectral analysis, a low-energy limit of 0.5 keV is used to minimize the calibration uncertainties in low energy.

1 At http://cxc.harvard.edu/contrib/alexey/tgain/tgain.html.
2 At http://cxc.harvard.edu/contrib/maxim/bg/index.html.
3 At http://cxc.harvard.edu/cal/ACIS/Cal_prods/qeDeg/index.html.
2.2. The Spatial Properties of the NGC 1265 X-Ray Source

Despite the gigantic extent (>40′) of NGC 1265 in the radio (O'Dea & Owen 1986; Sijbring & de Bruyn 1998), its X-ray extent is tiny (~10′), as shown in Figure 1. The X-ray emission is composed of a central point source and diffuse emission. The central point source is located within 0′1 of the nucleus determined from the HST observation (Fig. 1b). The soft X-ray emission (0.5–1.5 keV) is asymmetric, with a sharp edge 3″ south of the nucleus and an extension to the north. The asymmetry is quantitatively shown by the 0.5–1.5 keV surface brightness profiles (exposure corrected) along the south, north, and east-west sectors (Fig. 2). The sectors are defined in the caption of Figure 2. The 0.5–1.5 keV surface brightness profiles in the east and west differ very little, so we combine them. The surface brightness to the south decreases rapidly at ~2″5 and reaches the background level beyond ~3″, while the brightness profile to the north shows excess above the local background to at least 2″6. This morphology implies that the X-ray source is moving toward the south and indicates the action of ram pressure by the surrounding ICM. The azimuthally averaged profile is flat beyond 30″, which marks the local background level.

The nuclear point source dominates the hard X-ray emission (Fig. 1a). As there is no statistically important difference on the 2–6 keV surface brightness profiles in the south and north, only the azimuthally averaged profile is shown (Fig. 2). The point-spread function (PSF) of the central point source was derived with the Chandra Ray Tracer (ChaRT), assuming the best-fit absorbed power-law spectrum derived from the spectral analysis (discussed in § 2.3). Since the X-ray source is only 7′1 from the optical axis of the observation, the PSF is symmetric. In the 0.5–1.5 keV band, the PSF size is much smaller than the source size (Fig. 2). In the 2–6 keV band, a model with the PSF plus the local background matches the data well within the inner ~1″6 but underestimates the observed brightness of 2″–8″ at a level of 5.2 σ. This hard X-ray excess is indicative of low-mass X-ray binary (LMXB) emission in NGC 1265, which will be discussed next.

We assume that the LMXB light profile follows the stellar light profile, which is derived from the HST observation. A bright star 3″ east of the nucleus distorts the galaxy image and affects the ground photometry of the galaxy. The center of the star is saturated in the HST F702W image but not in the F673N image. We subtract the star light and derive the light profile of the galaxy. The galaxy contributes 70% of the total light in the F702W image.

In the soft band, the LMXB light distribution is the 0.5–1.5 and 2–6 keV bands are shown in Figure 2. In the hard band, a model with a central AGN (PSF), local background, and LMXB light roughly reproduces the data but overestimates the observed emission by ~15%. In the soft band, the LMXB emission is able to account for the emission beyond 9″, where the surface brightness profile is much flatter than that within 9″. However, as the LMXB light does not blur the southern sharp edge (Fig. 2), the LMXB emission must be discrete and be dominated by those
The ground spectrum was extracted from the 17\degree X-ray–bright region is considerably smaller (Fig. 1). The back-

corona. The region is chosen to enclose all X-ray emission of

 brightest binaries. In the following, we constrain the spectral properties of the X-ray source and the gas properties of the
corona.

2.3. The Spectral Properties of the NGC 1265 X-Ray Source

The spectral properties of the NGC 1265 X-ray source were measured. In view of the asymmetry, we extracted the global spectrum from a 10\degree radius circle centered 4\degree north of the nucleus. The region is chosen to enclose all X-ray emission of NGC 1265 above the local background (Fig. 2), although the X-ray–bright region is considerably smaller (Fig. 1). The background spectrum was extracted from the 17\degree–73\degree annulus centered on the nucleus. We first used a model with two components (POWERLAW+MEKAL). If only Galactic absorption is applied, the fit is acceptable but the nuclear source has an unusually flat spectrum (Table 1). The presence of a dust lane on the HST image may imply extra absorption around the central source. Thus, we allowed additional absorption for the POWERLAW component. As shown in Table 1, the fit is much improved and the de-

ic absorption column (besides the Galactic value of 14 × 10^{21} \text{ cm}^{-2}) for the nuclear source.

* The global spectrum of the NGC 1265 X-ray source, while the center is shifted to 4\degree north of the nucleus to account for the asymmetric morphology of the corona. The background is from the surroundings (all the same for corona emission; see text).

* The surrounding ICM emission, centered on NGC 1265’s nucleus, with the blank sky background excluded.

<1.6\degree center to 4\degree north of the nucleus to account for the asymmetric morphology of the corona. The background is from the surroundings (all the same for corona emission; see text).

<1.6\degree center to 4\degree north of the nucleus to account for the asymmetric morphology of the corona. The background is from the surroundings (all the same for corona emission; see text).

North extension

16\degree–90\degree

3.2

<1.6\degree (deprojected)

1.6\degree–10\degree

<10\degree (total)

1021 cm

<10\degree (total)

1021 cm

<10\degree (total)

1021 cm

<10\degree (total)

1021 cm

<10\degree (total)

1021 cm

a The excess absorption column (besides the Galactic value of 14 × 10^{21} \text{ cm}^{-2}) for the nuclear source.

b The global spectrum of the NGC 1265 X-ray source, while the center is shifted to 4\degree north of the nucleus to account for the asymmetric morphology of the corona. The background is from the surroundings (all the same for corona emission; see text).

c Centered on the nucleus.

d The annulus centered on the nucleus. A 8 keV bremsstrahlung component is included to model the contribution from LMXB.

e The global region excluding the central 1\degree (radius) region. A 8 keV bremsstrahlung component is included.

f The region is defined as the north half of a 3\degree x 8\degree (east-west semimajor axis times north-south semimajor axis) ellipse cen-
tered 1\degree north of the nucleus, excluding the region within 2\degree radius of the nucleus. A 8 keV bremsstrahlung component is included.

g The surrounding ICM emission, centered on NGC 1265’s nucleus, with the blank sky background excluded.

h The integrated ICM emission on the S3 CCD field.

TABLE 1

Spectral Fits of the NGC 1265 X-Ray Source

| REGION | T (keV) | Z (\%) | N_H (10^{22} \text{ cm}^{-2}) | \Gamma | \chi^2/\text{dof} |
|--------|---------|--------|-------------------------------|-------|-----------------|
| <10\degree (total) | 0.62 \pm 0.02 | 1.2 \pm 0.6 | \ldots | 1.3 \pm 0.3 | 64.1/74 |
| <1.6\degree | 0.51 \pm 0.04 | 0.9 \pm 0.2 | \ldots | 1.8 \pm 0.3 | 63.3/73 |
| <1.6\degree (deprojected) | 0.63 \pm 0.03 | 1.2 \pm 0.6 | \ldots | 2.0 \pm 0.3 | 34.7/42 |
| 1.6\degree–10\degree | 0.69 \pm 0.04 | 1.0 | \ldots | 1.9 \pm 0.3 | 36.1/42 |
| North extension | 0.76 \pm 0.07 | 1.0 | \ldots | \ldots | 23.7/31 |
| 16\degree–90\degree | 6.67 \pm 0.70 | 0.41 \pm 0.41 | \ldots | \ldots | 102.6/113 |
| S3 CCD | 6.41 \pm 0.25 | 0.48 \pm 0.10 | \ldots | \ldots | 192.0/143 |

| CHANNEL ENERGY (keV) | 1 | 2 | 3 | 4 | 5 |
|----------------------|---|---|---|---|---|
| PHOTONS/S/10^{-14} | \text{cm}^{-2}\text{ keV}^{-1}\text{ s}^{-1} | \text{cm}^{-2}\text{ keV}^{-1}\text{ s}^{-1} | \text{cm}^{-2}\text{ keV}^{-1}\text{ s}^{-1} | \text{cm}^{-2}\text{ keV}^{-1}\text{ s}^{-1} | \text{cm}^{-2}\text{ keV}^{-1}\text{ s}^{-1} |

FIG. 3.—Spectra of the inner (<1.6\degree) and outer (1.6\degree–10\degree) regions of the NGC 1265 X-ray source, with the two-component models shown as the fourth and the seventh rows in Table 1 (dot-dashed line: corona emission; dashed line: absorbed nuclear emission or LMXB emission; solid line: the sum). The blend of iron L lines is significant in both spectra. The shapes of the spectra at E > 1.5 keV are different. The absorbed nucleus dominates in the hard X-rays for the inner region, while the LMXB is a significant component for the outer region.
(90% confidence level). The allowed abundance change and the inclusion of the hard component do not affect the robustness of the temperature measurement.

We derived the deprojected temperature of the inner region (the fifth row in Table 1) with the standard nonparametric “onion-peeling” technique. The spectral properties of the 1r6–3r2 annulus, where the X-ray emission is still rather symmetric, were also examined (the sixth row in Table 1). Gas temperature decreases from 0.7 keV at the outskirts to 0.45 keV within the central 0.6 kpc high-density core, implying the action of radiative cooling. As shown in Figure 2, the central point source also accounts for some emission in the outer region (∼29%), and there may be LMXB emission within 1r6 at the level of ∼5%. However, these extra components require little change in the fits and computed parameters (including luminosities). The best-fit absorption excess for the AGN is ∼2 × 1022 cm−2. The 2–10 keV bolometric and bolometric luminosities of the central AGN are 5.5 × 1040 and 3.0 × 1041 ergs s−1, respectively. The 0.5–2 keV bolometric luminosities of the corona are 3.3 × 1040 and 4.8 × 1040 ergs s−1, respectively. The 0.3–10 keV luminosity of the 1r6–10′′ LMXB component is 1.8 × 1040 ergs s−1.

We also examined the spectral properties of the north extension. Its spectrum was extracted from the region defined in Table 1. The result confirms that the north extension is from the emission of thermal gas, while the LMXB component only contributes to ∼5% of the 0.5–1.5 keV counts there. The soft X-ray luminosity of the 1r6–10′′ region, the contribution drops to 10% in a smaller region, enclosing the entire soft X-ray–bright region (a 6r5 radius circle centered at 3r2 north of the nucleus). Thus, the 0.5–1.5 keV surface brightness well delineates the morphology of the soft corona.

2.4. The Properties of the Surrounding ICM

We need to know the properties of the surrounding ICM to study the corona-ICM interaction. If NGC 1265 is on the plane of the sky (27′ from the cluster center), the electron density of the surrounding ICM is 5.9 × 10−4 cm−3 according to the ROSAT data (Ettori et al. 1998). If the galaxy is within 20′ (or 439 kpc) of the plane of the sky along the line of sight, the ICM density is >4.1 × 10−4 cm−3. We adopt a typical ICM electron density of 5 × 10−4 cm−3 in this work but keep the uncertainty in mind. The spectrum of the surrounding ICM (16′′–90′′) is studied, as well as that of all of the ICM emission on the S3 CCD. The surrounding ICM (projected) is 10 times hotter (∼6.7 keV; Table 1) than the small galaxy corona (∼0.6 keV). The Chandra ICM temperature is consistent with the ASCA value for this region (Furusho et al. 2001).

2.5. The Gas Distribution of the NGC 1265 Corona

We want to characterize the gas distribution of the corona in different directions with the derived 0.5–1.5 keV surface brightness profiles. The contribution of the nuclear emission to the soft band and the LMXB emission have to be subtracted. The first component is derived from the PSF and the spectral fits in § 2.3, while the LMXB component is estimated from the optical light. Both components are small contributions to the total X-ray emission within 8′′. The LMXB component in the south sector is not subtracted, as the scaled LMXB light from the optical light largely overestimates the actual LMXB light beyond 3′′ in the south. Nevertheless, any LMXB contribution to the bright core within 2′′ is small. Since the X-ray source is so small, the Chandra PSF has to be considered in the fits. We applied a model composed of a β model plus a constant background for profiles in the south, north, and east-west, as well as the azimuthally averaged profile. We also tried to apply a truncation radius to the β model, especially for the southern profile. The results are shown in Table 2. Without a truncation radius, the fit to the southern profile yields an unphysical β (≥10), which is thus not shown. The fits to the profiles in the south and north are shown in Figure 4. The southern profile is clearly truncated at the sharp edge (2′2 ± 0′3 south the nucleus), with a large jump of surface brightness across the edge (∼106), while the truncations in other directions are not significant, with a small surface brightness jump of <3–5. Despite the large uncertainties, gas distributions (assuming the same emissivity) in all directions are consistent with the same distribution, but with different truncation radii (or no truncation). We also constrain the width of southern edge by smearing the truncated β model with a Gaussian exp(−r2/2 σ2). The best-fit model requires σ = 0 and the 95% upper limit of σ is only 0.2 kpc. We can compare the NGC 1265 corona with the two large coronae in A1367 (S05). Both luminous coronae in S05 are largely symmetric, and the surface brightness jump across the presumably pressure-confined boundary is at most 4–9. Thus, the sharp edge only 2′2 (or 0.81 kpc) south of the NGC 1265 nucleus is certainly unique and cannot be explained by the confinement of the static ICM pressure.

The gas density and mass can be derived from the surface brightness distribution. The best-fit thermal models of the inner and outer regions give almost identical emissivity if the metallicity is chosen the same. For simplicity, we assume a constant metallicity and a constant emissivity for the whole corona. In view of the unsymmetrical shape of the NGC 1265 corona, we applied

| Direction | rc (arcsec) | β | rcaut (arcsec) | SX Jump (at rcaut) | fback (10−6 counts s−1 arcsec−2) | χ2/dof |
|-----------|------------|---|----------------|------------------|----------------------------------|-------|
| South     | 1.5 ± 0.5  |    | 2.2 ± 0.3      | ~106             | 1.90 ± 0.14                      | 7.5/9 |
| North     | 1.5 ± 0.5  | 0.74 ± 0.09 | ...           | ...               | 1.58 ± 0.15                      | 17.2/18 |
| East-west | 2.8 ± 0.4  | 0.69 ± 0.10 | 8.1 ± 0.04     | ~4.8              | 1.66 ± 0.13                      | 17.9/17 |
| All       | 1.29 ± 0.09 | 0.77 ± 0.04 | 6.3 ± 0.6      | ~4.0              | 1.70 ± 0.09                      | 16.6/12 |

Notes.—The β model fits to the 0.5–1.5 keV SX in different directions (truncated or not). The local PSF is included in the fits. The value fback is the flux of the local background, which slightly decreases from the south (closer to the cluster center) to the north.
two methods to derive the density profile and the total gas mass. The first is to use the fit to the azimuthally averaged 0.5–1.5 keV profile derived above. Assuming a metallicity of 0.5–1.5 solar, the central electron density is 0.28–0.48 cm$^{-3}$, and the total gas mass is $(3.2–5.4) \times 10^7 M_\odot$ (within $r_{\text{cut}}$ of 7.7 kpc). The second method is to assume that the corona is composed of two hemispheres characterized by the surface brightness profiles of the south and the north, respectively. Assuming a metallicity of 0.5–1.5 solar, the central electron density is 0.22–0.37 cm$^{-3}$, and the total gas mass is $(2.4–4.2) \times 10^7 M_\odot$ (within $r_{\text{cut}}$). Thus, the central electron density of the corona is 0.22–0.48 cm$^{-3}$, and the total gas mass is $(2.4–5.4) \times 10^7 M_\odot$. Assuming a central abundance of 0.5–1.5 solar, the central gas cooling time is only 5–15 Myr.

With the derived gas density profile, the X-ray interstellar medium (ISM)-ICM pressure ratios are $24 \pm 16$ at the southern edge and $1.8^{+1.2}_{-0.5}$ at the end of the northern tail. Although the errors are large, the values indicate that the static ICM pressure is not enough to produce the southern sharp edge.

2.6. X-Ray Emission from the Jets

X-ray emission, at the significance levels of 2.2–3.6 $\sigma$, is found at the positions of three radio inner knots in the jets (E1, E2, and W1 from O'Dea & Owen 1986). A total of $\approx 28$ counts are collected from these three knots. Assuming a power-law spectrum with a photon index of 2.0, the $0.5–10$ keV luminosities are $\sim 1.1 \times 10^{38}$, $6 \times 10^{38}$, and $5 \times 10^{38}$ ergs s$^{-1}$ for E1, E2, and W1, respectively. Recent Chandra observations show that an X-ray jet is common in galaxies with radio jets (e.g., Worrall et al. 2001; Sambruna et al. 2004). However, this deep observation of NGC 1265 implies that the X-ray jet can be very faint in some cases (at least 40 times fainter than the faintest jet in Worrall et al. 2001). We estimate the 1 keV X-ray to 8 GHz radio flux density ratio over the X-ray–detected regions of the jet to be $\sim 10^{-8}$, which is smaller than what is generally found for low-power radio galaxies in which the jet X-ray emission is considered as synchrotron emission ($\sim 10^{-6}$; see the list in Evans et al. 2005). The nondetection of NGC 1265’s optical jet also argues against the synchrotron interpretation.

In spite of the nondetection of the continuous X-ray jets, there are spatial indentations east and west of the corona (Fig. 1a) that are aligned with the radio jets. These features imply interaction between the narrow jets and the X-ray corona. The widths of the indentations are comparable to the widths of the radio jets.

3. DISCUSSION

3.1. The X-Ray Edge and the Velocity of NGC 1265

The sharp X-ray edge is a strong indication of the ISM-ICM interaction. The mean free paths of particles near the edge are $l_{\text{ICM}} = 27$ kpc, $l_{\text{ISM}} = 1.5 \left(n_e / \text{cm}^{-3}\right)^{-1}$ pc, $l_{\text{ICM-ISM}} = 60 \left(l_{\text{ISM}}/1.5\right)$ pc, and $l_{\text{ICM-ISM}} = 5.4$ kpc, assuming temperatures of 6.7 and 0.7 keV for the ICM and the ISM near the edge, respectively. As $l_{\text{ICM}}$ is much larger than the size of the corona ($\approx 4$ kpc in diameter), the ICM may not be treated as fluid relative to the corona. Furthermore, as the galaxy with stars only is rather porous and the corona is so small, it is questionable whether a bow shock can be generated ahead of the corona as the source of the change in the fluid pattern there. A collisionless bow shock may still be generated, as implied by the weak 92 cm emission detected ahead of the X-ray edge (Sijbring & de Bruyn 1998), but this depends on the magnetic field structure around the corona. The magneto-hydrodynamic (MHD) interaction between the galactic magnetic field and the ICM particles (and the magnetic field frozen into them) is, however, poorly understood. The value of $l_{\text{ICM-ISM}}$ derived above is much larger than the width of the edge ($<0.2$ kpc), which can only be understood if the actual mean free paths of particles are largely suppressed by the magnetic field at the ICM-ISM boundary. Recent simulations of gas stripping and the evolution of X-ray coronae in clusters (e.g., Tonizzo & Schindler 2001; Acraman et al. 2003) were undertaken in an attempt to study the problem using only fluid dynamics, but they did not address the small sizes of X-ray coronae or the inclusion of MHD physics. The observed properties of the NGC 1265 corona demonstrate that it is necessary to include magnetic fields, especially for small coronae moving in the hot clusters, as the mean free path of particles is sensitive to temperature ($\propto T^2/n$).
Our knowledge of the magnetic field in elliptical galaxies is poor (reviewed by Widrow 2002). Moss & Shakur (1996) proposed two types of seed fields in elliptical galaxies: stellar magnetic fields ejected by supernovae (SNe) and stellar winds; and magnetic remnants that arise if elliptical galaxy forms from mergers of spirals. These seed fields have to be amplified by dynamo. They proposed two types of dynamos: acoustic turbulence driven by SNe Ia and stellar winds; and vortical turbulence driven by stellar motion. Since the magnetic Reynolds number is large, the amplified magnetic field should be frozen in the gas (or the hot gas in elliptical galaxies). When the galaxy falls into the dense ICM, the galactic magnetic field may be compressed and stretched at the boundary, which would be responsible for the suppression of transport processes. However, this simple picture may be too naive as a lot of details remain unclear. Moreover, the small corona of NGC 1265 is surrounded by the hot ICM filling the NGC 1265 galaxy. How the field within the corona can be magnetically isolated from the field in the surroundings (still in the galaxy) is unclear, especially if the turbulent diffusion of magnetic field is important (e.g., Lesch & Bender 1990).

Assuming that the radial velocity difference of NGC 1265 and the Perseus cluster is NGC 1265’s radial velocity relative to the cluster, the velocity of NGC 1265 ($v_{\text{gal}}$) is 2170/cosθ km s$^{-1}$, where θ (between 0° and 90°) is the angle between the line of sight and the opposite of the moving direction. The radial velocity dispersion of the Perseus cluster is 1324 km s$^{-1}$ (Struble & Rood 1999), which corresponds to a three-dimensional velocity dispersion of 2293 km s$^{-1}$ (σ). NGC 1265’s velocity cannot be too high (e.g., 3 σ; or 6880 km s$^{-1}$, θ = 71.6°) for the galaxy to remain bound.

The sharpness of the X-ray edge implies that θ is not small. Otherwise, the edge would be smeared by projection. In principle, we can use the sharp X-ray edge to constrain the velocity of the galaxy. This first requires a good understanding of projection. We performed a number of simulations. The shape of the corona is assumed to be prolate, with the nucleus at the center. Since the front of the corona is ablated and compressed by ram pressure, the front is approximated by a large sphere cut by the prolate ellipsoid, while the center of the sphere lies north of the nucleus. The small corona is assumed to be axially symmetric to the direction of the motion. The coronal density profile is represented by a β model with a truncation at the boundary of the corona (see § 2.5). The projected morphology of the simulated corona matches the observed morphology well. We compare the projected profiles with the observed ones and find that the X-ray sharp edge cannot be preserved for $\theta < 45°$. As θ decreases from 90°, the front edge has to be shifted toward the nucleus to allow the projected edge to match the observation. Thus, the best-fit velocity increases as θ decreases, opposite from the dependence of velocity on θ from the radial velocity constraint. Therefore, the velocity can be in principle constrained well by these two methods. However, several uncertainties prevent a tight constraint on the velocity. First, there is a degeneracy between the ICM density and the galaxy velocity. Second, the coronal density can vary 70% for an abundance change of 0.5–1.5 solar. Finally, the MHD properties of the ICM are not known. For an ambient density of $5 \times 10^{-4}$ cm$^{-3}$, the best-fit angle is 50°–65° and the velocity is 3500–5000 km s$^{-1}$ if we treat the ICM as fluid. Two interesting facts are that (1) the surrounding ICM density is $>2 \times 10^{-4}$ cm$^{-3}$ if NGC 1265’s velocity is <5000 km s$^{-1}$ and the abundance of the corona is <1.2 solar; and (2) that the abundance of the corona has to be <3 solar (a tighter upper limit than that derived from the spectral analysis) for the ISM gas to be dense enough to withstand the ram pressure.

Combining these constraints, we conclude (conservatively) that $45° < \theta < 67°$ and 3100 km s$< v_{\text{gal}} < 5500$ km s$^{-1}$ (note that the local sound speed is $1.3 \times 10^3$ km s$^{-1}$).

### 3.2. The Evolution of the NGC 1265 Corona

As the corona moves through the ICM with $v_{\text{gal}}$ of $>3100$ km s$^{-1}$, it is subject to ram pressure stripping and other stripping processes by the surrounding ICM (e.g., Nulsen 1982). The analysis of ram pressure stripping in S05 ignores the high ISM pressure. The survival of NGC 1265’s corona in the face of high-speed ram pressure stripping and the presence of a sharp edge indicate that high thermal pressure of the inner cooling core is the key to preserve the corona from ram pressure stripping, although the outskirts of the corona are very vulnerable to stripping.

As was discussed in § 3.1, the physics around the small corona should be best described by MHD physics. The Kelvin-Helmholtz (K-H) instability may or may not be suppressed. Lacking a good understanding of the relevant physics, only a qualitative discussion is presented. No matter how we treat the surrounding ICM, as fluid or as particles, the typical mass-loss rate of the corona by K-H instability or by the bombardment of the ICM particles is approximately (e.g., Nulsen 1982)

$$\dot{M}_{\text{strip}} \approx \pi r^2 \rho_{\text{ICM}} v_{\text{gal}}$$

where $n_{e,\text{ICM}} = \frac{r}{2 \text{ kpc}}$ and $v_{\text{gal}} = \frac{3500 \text{ km s}^{-1}}{M_\odot \text{ yr}^{-1}}$.

This process acts at the boundary of the corona. We calculate the stellar mass injection rate in these two regions to be $<1/6$ and $1/6$–10. Using the generally adopted mass injection rate of $M_s = 0.15 M_\odot \text{ yr}^{-1}$ (Faber & Gallagher 1976) and the optical luminosity in the chosen region (from the HST data), we estimate 0.04 and 0.15 $M_\odot \text{ yr}^{-1}$ for the inner and outer regions, respectively. The mass deposition rate by cooling, $M \approx 2 \mu_{\text{p}} L_{\text{bol}} / 5 k T$, is calculated in each region to be 0.19 and 0.16 $M_\odot \text{ yr}^{-1}$. Thus, in the inner region the mass deposition rate is higher than the expected stellar mass injection rate, while in the outer region the expected mass-loss rate by stripping is comparable (if not higher, because of the uncertainties from equation [1]) to the expected stellar mass injection rate. Although the mass loss by stripping decreases rapidly to approximately less than the stellar injection at radius $<1/10$–1/6, the cooling rate changes little if there is no feedback on this small scale. The estimated lifetime of the current corona is then only 0.1–0.2 Gyr.

There are several factors that can reduce the effects of stripping and offset cooling to help the corona to survive much longer. First, the stripping by transport processes can be suppressed by the magnetic field. Second, stellar mass injection is a key (e.g., shown in the simulations by Acreman et al. 2003). While the Faber & Gallagher (1976) result is an average, the host galaxies with surviving coronae may have systematically larger stellar mass injection rates than the average. Stellar mass injection outside the corona can also affect the ICM flow pattern there, although the injected ISM gas is not likely to sink into the corona before being stripped and mixed with the ICM. For NGC 1265, if we compare the mass-flow rate of the ICM and the expected stellar mass injection rate outside the corona upstream, on the cross-section of the corona, the latter is only ~10% of the ICM mass flux and is not likely to be a significant factor. However, combined with the galactic potential, magnetic field, and stellar motion, the ICM flow inside the galaxy (but outside the corona) should be much more complicated than the free flow far away from the
power of its jets can be estimated (e.g., Jones & Owen 1979). We assume that the jet flow is nonrelativistic, while the power of relativistic jets is much larger. From Euler’s equation, we have \( P_j \approx \frac{\rho v_j^2}{C_{24}} \), where \( \rho \) is the particle density in the jet, \( v_j \) is the velocity of the jet flow, \( r_j \) is the radius of the jet, \( R \) is the radius of curvature of the bent jet, and \( P_{\text{ran}} \) is the IC ram pressure. The kinetic power of jets is \( L_K \approx \frac{\pi r_j^3 v_j^3}{C_{25}} \). With the relation from the bending of jets and adopting \( r_j = 1 \) kpc, \( R = 12 \) kpc (from the radio image), \( v_j = 10^4 \) km s\(^{-1}\), \( n_e_{\text{ICM}} = 5 \times 10^{-4} \) cm\(^{-3}\), \( v_{\text{gal}} = 3500 \) km s\(^{-1}\), and \( L_K = 4.3 \times 10^{43} \) ergs s\(^{-1}\). The value of \( r_j \) could be smaller but that of \( v_{\text{gal}} \) may be larger. Their product should not change significantly based on the relation from the bending of jets. The energy in the magnetic field is only \( \sim 10^8 \) to \( 25\% \) of \( L_K \) if the minimum pressure magnetic field is adopted (20–30 \( \mu G \); from O’Dea & Owen 1987). The AGN has been active for \( >10^8 \) yr from the length of the tail. We estimate that the total jet power over the active phase of the nucleus is at least 1600 times the thermal energy in the current corona. In view of the great vulnerability of the current corona to AGN feedback, we conclude that the jets carry a great amount of energy without dissipation through the small corona, as we previously suggested in S05 for weaker radio sources associated with the coronae in NGC 3842 and NGC 4874.

The interaction of jets and X-ray plasma is strongly suggested by the small X-ray indentations 25 east and west of the nucleus (Fig. 1). The radio emission of the jets is anticorrelated with the X-ray emission of the corona (Fig. 1), as the radio emission of the jets turns on after they leave the dense corona. The jets may undergo a transition after they leave the dense corona, possibly because of the change in the external pressure. The coronal thermal pressure, \( 1.9 \times 10^{-10} \) (\( n_e/0.1 \) cm\(^{-3}\) (\( kT/0.6 \) keV) dynes cm\(^{-2}\), is larger than the minimum pressure in the inner knots of the jets, \( 6 \times 10^{-11} \) dynes cm\(^{-2}\) (O’Dea & Owen 1987), while the ICM thermal pressure is only \( 10^{-12} \) dynes cm\(^{-2}\). Thus, the ISM thermal pressure may be enough to confine the jets, while the ICM pressure may not be. The edge brightening of the jets from the first knots implies the action of ram-pressure (O’Dea & Owen 1986). The jets are clearly bent by the ICM ram pressure, rather than the pressure gradient in the ISM, as originally suggested by Jones & Owen (1979).

If the dense core of the corona cools, the cooling product may feed the central SMBH. The stellar velocity dispersion of NGC 1265 is unknown. Using the Faber-Jackson relation and the \( M_{\text{BH}}-\sigma \) relation (Tremaine et al. 2002), the mass of the SMBH at the nucleus of NGC 1265 is \( \sim 5 \times 10^8 M_\odot \). Assuming this mass and a central gas temperature of 0.45 keV, the Bondi accretion radius of the central SMBH is 36 pc (or 0″1) if the surrounding corona gas has little residual bulk motion relative to the SMBH. The Bondi accretion rate and the accretion luminosity are 0.0031 \( M_\odot \) yr\(^{-1}\) and 1.8 \( \times 10^{43} \) ergs s\(^{-1}\) (assuming a radiation efficiency of 0.1) for a central electron density of 0.3 cm\(^{-3}\). The Bondi accretion luminosity is known to largely overestimate the luminosity of many low-luminosity AGNs (e.g., Loewenstein et al. 2001). Possible explanations include that the accretion process is radiation inefficient and other processes (e.g., feedback) reduce the Bondi accretion rate significantly (e.g., Gliozzi et al. 2003).

4. CONCLUSION

The main results of this deep observation of the prototype NAT galaxy NGC 1265 are as follows:

1. A small (\( \sim 4 \) kpc) and asymmetric thermal corona is detected around the nuclear region of NGC 1265. A sharp edge is
found $2''$ (0.8 kpc) south of the nucleus, while a $\geq 8''$ extension is present to the north. This indicates high-velocity motion of NGC 1265 toward the south on the plane of sky, which is consistent with the long radio tail to the north.

2. The southern edge is very sharp, with a jump of surface brightness of $\sim 106$ and a width of $\lesssim 0.2$ kpc. As the mean free paths of particles in the ICM (27 kpc) and from the corona to the ICM (5.4 kpc) are much larger than the width of the edge, a magnetic field around the edge is required to significantly reduce the particle diffusion. The interaction between the small coronae and the ICM must be studied by MHD physics.

3. The temperature of the coronal gas decreases from 0.7 keV at the outskirts to 0.45 keV at the center, while the temperature of the surrounding Perseus ICM (projected) is $\sim 6.7$ keV. The coronal abundance is consistent with solar. The 0.5–2 keV luminosity of the corona is $3.3 \times 10^{40}$ ergs s$^{-1}$. The central electron density is $\sim 0.22$–0.48 cm$^{-3}$, while the total gas mass is $\sim 4 \times 10^{7} M_{\odot}$.

4. An absorbed ($N_{H} = 1.5 \times 10^{22}$ cm$^{-2}$) low-luminosity X-ray nucleus is detected, with a 2–10 keV luminosity of $\sim 5.5 \times 10^{40}$. This amount of high nuclear absorption column is not usual for FR I radio galaxies.

5. Three inner radio knots are detected in X-rays. Indentations east and west of the corona indicate the interaction between jets and hot gas. There is an anticorrelation between the emission of the radio jets and the X-ray corona (Fig. 1). This implies that jets undergo a transition as they leave the dense corona.

6. The great vulnerability of NGC 1265’s corona to the very powerful jets from the central SMBH implies that the AGN deposits all its energy outside the current corona. This also may imply that AGN heating cannot quench the cooling very close to the nucleus (within several kpc) in “cooling-flow” clusters.

7. Constraints from the radial velocity and the X-ray edge yield a velocity for NGC 1265 between 3100 and 5500 km s$^{-1}$, and the angle between the tail and the line of sight is $45^\circ$–$67^\circ$.

8. If the stripping, cooling, and evaporation are not suppressed, the current corona can only survive for 0.1–0.2 Gyr. However, enhanced stellar mass injection, suppressed stripping, and SN Ia heating (if the energy is coupled to the hot gas) can significantly increase the lifetime of the corona. For the survival of NGC 1265’s corona, heat conduction has to be suppressed by at least a factor of $60$ at the ICM-ISM interface.

The survival of NGC 1265’s corona from ram pressure stripping implies that coronae of similar or more massive galaxies can survive $\geq 1000$ km s$^{-1}$ stripping in environments like the core of the Coma Cluster. A systematic study based on Chandra data is underway, which will help us better understand the evolution of these small coronae in rich clusters, including their fates, the fueling of the SMBH, their interaction with the environment, and their relation with large cooling cores.

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