CHANDRA OBSERVATION OF THE LOW ENTROPY REGION IN THE RADIO LOBE GALAXY NGC 1316

Makoto Tashiro[1], Kouichi Ito[1], Keiichi Abe and Naoki Isobe[2]

[1]*Department of Physics, Saitama University, 255 Shimo-Okubo, Sakura, Saitama, 338-8570, Japan*
[2]*Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan*

ABSTRACT

NGC 1316 hosts the classical double lobe radio galaxy Fornax A. Recently, Kim and Fabbiano (2003) revealed with *Chandra* a 'blob' like emission associated with the optical dark lane, suggesting heating by the galaxy-merging. In this paper, we show a detail analysis focusing into the 'blob' to show significantly low temperature and low entropy. The significantly lower entropy in comparison with the other inter-stellar medium structures supports that the 'blob' are produced at the past galaxy merging. Comparing with those of non-thermal electrons in the radio lobes, we discuss a possible history of the nucleus activity and show its estimated kinetic luminosity during its active phase.

Key words: X-ray: galaxies --- X-rays: active nucleus ---galaxies: individual (NGC 1316)

1. INTRODUCTION

Formation of super massive black holes and history of the resultant active galactic nuclei is a crucial issue to evaluate total energy flow from galaxies and galactic medium heating. Some observational constraints, based on black hole merging models, estimate the lifetime of active galactic nuclei (AGNs) to be 0.01 to 0.1 Gyr (e.g. Yu & Tremaine 2002). In addition, recent observational results show that kinematic energy flows from the AGNs could be comparable to those of radiative energy (e.g. Isobe et al. 2005; I05 hereafter). That estimation implies that AGNs with large scale jets may have injected kinetic energy of $10^{58\text{-}61}$ergs into the inter-galactic space through their life. It suggests that it is important to estimate the lifetime of outflow activity independently from their electromagnetic radiation to evaluate total energy output from AGN to the inter-galactic medium.

In this paper, we present X-ray observation results from the radio galaxy Fornax A (NGC 1316), having prominent double lobes with the dimmed nucleus. The host galaxy NGC 1316 is a disturbed elliptical galaxy with numerous tidal tails. Schweizer (1980) suggested that the morphology is caused by several low-mass, gas-rich merging over the last 2 Gyr (see also Ekers et al. 1983; Kim, Fabbiano, & Mackie 1998; Mackie & Fabbiano 1998). Fornax A (NGC 1316) has been extensively observed in a wide range of wavelengths. In the radio band, Fornax A is the third brightest object in the sky, with giant radio lobes (Wade 1961; Ekers et al. 1983), separated by 200 kpc, consisting of polarized filaments (Fomalont et al. 1989) and S-shaped nuclear radio jets (Geldzahler & Fomalont 1984). In X-ray band, the galaxy was observed intensively so far with *Einstein* (Fabbiano, Kim, & Trinchieri 1992), *ROSAT* PSPC(Feigelson et al. 1995), *ASCA* (Kaneda et al. 1995; Iyomoto et al. 1998; Tashiro et al. 2001), *ROSAT* HRI (Kim, Fabiano & Makie 1998), *Chandra* (Kim & Fabbiano 2003: KF03 hereafter) and *XMM-Newton* (Isobe et al. 2005: I05 hereafter).

In particular, the *ROSAT* observations revealed ~10^9 $M_{\rm solar}$ of hot ISM, with an inhomogeneous distribution. Although the substructures of the ISM were not highly significant, given the *ROSAT* HRI data quality, KF03 confirmed the presence of fine substructures in the hot interstellar medium (ISM) with *Chandra*. Some of the substructures are likely to result from interaction with the radio jets, while others placed free from the jet directions should be related to a complex intermingling of different phases of the ISM. They also confirmed the dimmed nucleus with $L_x = 5\times10^{39}$ ergs s^{-1} (in 0.3 to 8 keV band) and a Γ=1.7 power-law energy spectrum, which is consistent with the results reported by Iyomoto et al. (1998).

X-ray observations with *ASCA* (Kaneda et al. 1995; Iyomoto et al. 1998; Tashiro et al. 2001), *ROSAT* (Feigelson et al. 1995), and *XMM-Newton* (I05) have also been unveiling the inverse-Compton X-rays from the lobes. In particular, I05 summarized them and revised electron energy and the energy density spectrum based on the latest X-ray and radio results.

In this paper we reanalyze the *Chandra* observation results on the possible merging induced ISM to compare its cooling time scale with the suggested history of the lobes. Also discussion on the lobe cooling time derived from the X-ray observation of

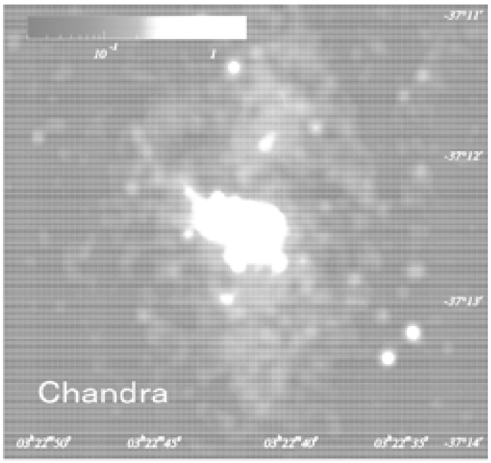

Figure1. Chandra 0.2-7keV image of NGC1316

lobes is presented in comparison with the newly estimated cooling time of the ISM structure.

2. OBSERVATION AND RESULTS

2.1 Observation

NGC 1316 was observed for 30 ks on 2001 April 17 (Observation ID 2022), with the *Chandra* Advanced CCD Imaging Spectrometer (ACIS; Garmire 1997), and details are described by KF03. We reanalyzed the archive data and processed them thoroughly with the latest processing tools and calibration files.

2.1 Results from Point Sources

We show the obtained 0.2 to 10 keV X-ray image in Fig. 1, in which we smoothed the image with two-dimensional Gaussian function of $\sigma = 4$ pixels. We see elongated emission in the north-south direction. It extends within the optical galaxy and the direction is perpendicular to the lobe axis (east-west). KF03 noticed the 'blob' like ISM substructure, exhibiting a prominent peak emission in the north of the galaxy centre.

We show the X-ray band images in Fig. 2. They are labelled with (a) to (d) each of which represent 0.2-0.7, 0.7-1.2, 1.2-2.0 and 2.0-5.0 keV band images, respectively. We see the significant substructures at the galaxy centre and the north-south extension in the softer two band images, although no significant diffuse emission in the harder bands.

Before investigating the diffuse emission structure, we note we see no prominent peak at the centre of the galaxy. In order to evaluate the possible active nucleus

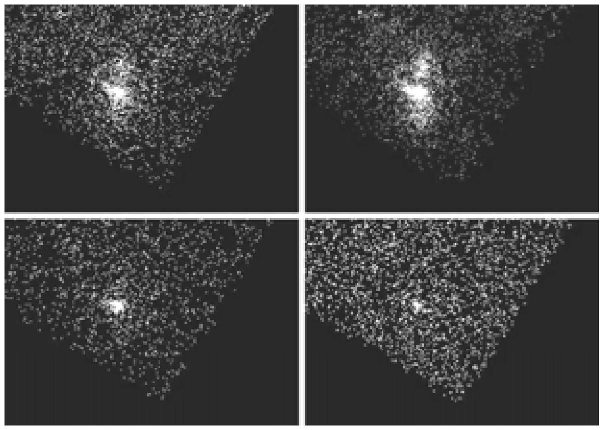

Figure 2. Chandra X-ray band images from NGC1316 (a)0.2-0.7, (b) 0.7-1.2, (c) 1.2-2.0, (d) 2.0-7.0 keV (see text).

emission, we accumulate photons within 250 pc from the centre. Although the obtained spectrum is well described with power-law model, the best-fit photon index of 2.8 ± 0.24 is too soft to be attributed to the typical AGN emission. The derived upper limit of the luminosity from the centre region is up to 10^{40} erg s^{-1}, which is consistent with the reported values by Iyomoto et al. (1998) and KF03. We conclude that we observe no significant nucleus activity of the radio galaxy.

2.2 Results from Diffuse Emissions

Point sources in the field are investigated and reported by KF03. In order to focus into the diffuse emissions, here we remove all the point sources and evaluate the residual diffuse X-ray spectrum. As described by the previous report (e.g. Kaneda et al. 1995), whole galaxy is covered with wide spread emission from a relative hot component $kT = 0.83$ keV, which is known to be extended outside of the galaxy. Here we subtracted the large-scale thermal emission by employing background spectrum region outside but near the optical galaxy. In the following, we examine the spectra from the ISM substructures by employing regions shown in Fig. 3.

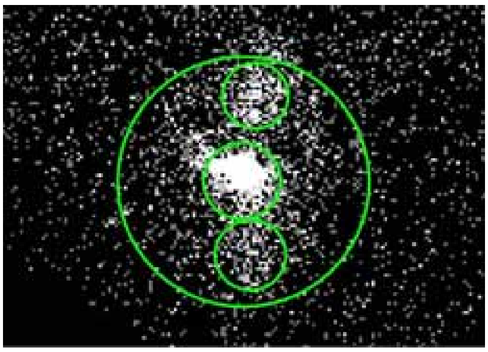

Figure 3. Spectrum accumulating regions for: (1) the north 'blob'; (2) the centre; (3) the south 'blob'; (4) diffuse ISM.

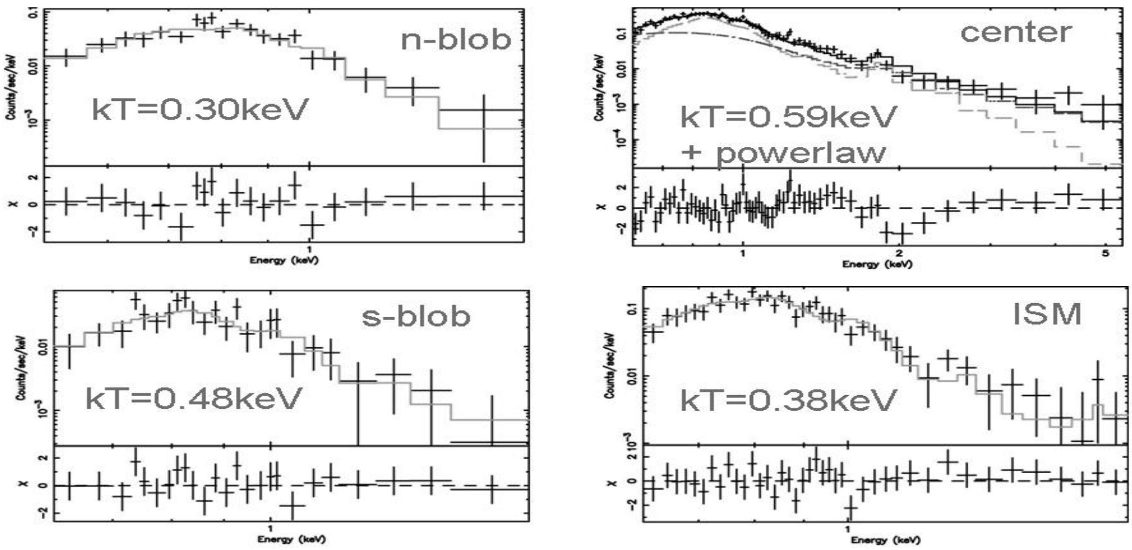

Figure 4. X-ray spectra obtained from the four regions.

The regions are; (1) north 'blob'; (2) central region of the galaxy; (3) southern extension also 'blob' like structure; and (4) diffuse ISM in the galaxy.

Thus integrated X-ray spectra are presented in Fig. 4. We used "mekal" model to evaluate the thermal emission and summarized the best-fit parameters in Table 1. All but the centre region spectra are well described with thermal plasma emission model. Only from the centre we detected an additional hard component. The hard component is here described with a power-law model, although it is thought to represent unresolved point sources including low mass X-ray binaries in the centre region.

Table 1. Summary of the spectral fitting for the diffuse emission regions

Region	kT (keV)	χ^2_{red}
1	0.30 +/- 0.02	0.87
2	0.59 +/- 0.02	1.12*
3	0.48 +/- 0.06	0.64
4	0.38 +/- 0.03	0.74

*: with additional power-law component (text).

3. DISCUSSION

3.1 Entropy of the ISM Substructures

We observed NGC 1316 having a large-scale double lobe without large-scale radio jets or active nucleus. We confirmed the ISM substructures suggested to be related with the past galaxy merging. Interestingly, the measured temperatures of the substructures are not homogeneous. We observed the hot plasmas in the centre and in the south extension, while we found the relative cool plasmas in the north blob and from the diffuse ISM region. The brightness and temperature profile imply inhomogeneous entropy distributions in the ISM substructures, and suggests different origins of each substructure. In this section, we calculate the 'entropy' to discuss a possible history of the nucleus activity in the following subsection. We here adopted the definition of 'entropy' (or adiabat) as,

$$S = n^{-2/3} kT \; , \tag{1}$$

according to Tozzi and Norman (2001). The calculated S for each region (region 1, 2 and 4) is summarized in Fig. 5 in reference to the radial distance from the centre of the galaxy. The grey line indicates the extrapolation from the outer ISM region in the case of gravitational cooling only ($S \propto r$). We note the derived entropy value for the central region exceeds the line. It might be caused by the heating at the merging or by subsequent nucleus activity. On the other hand, the lowest entropy of the north blob is consistent of the extrapolation if the blob were at the centre. The fact might hint that the blob used be at the centre.

3.2 Electron Energy in the Lobes

Referring to I03 presenting a new estimation of stored energy in the lobes, we adopt the derived energy densities of the relativistic electrons and the magnetic fields are $u_e = 2.8 \pm 0.3$ erg cm^{-3} and $u_m = 0.3^{+0.08}_{-0.06}$ erg cm^{-3}, respectively. Employing these values with estimated emission volume of the two lobes, we obtained a cooling time of 0.2 Gyr for both synchrotron and Compton processes.

3.3 Possible History of the Nucleus Activity

Indices of the end time of activity of the nucleus are given by those facts that the jets are extinguished; yet the relativistic electrons in the lobes have not been cooled. These give the lower and the upper limits of the time intervals from the end of activity to the present time, such as 0.1 Myr and 0.2 Gyr, respectively.

On the other hand, cooling times of the ISM sub-structures suggest the age of the merging galaxy. We calculate it as 1 Gyr from the cooling time of the north blob. Adopting these indices as the duration of the activity of the nucleus, we could conclude that it last, at the longest case, from 1 Gyr to 0.1 Myr ago at the rest frame of the galaxy.

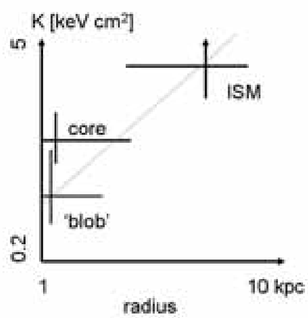

Figure 5. Radial entropy profile of the radio galaxy

The estimated total electron energy in the lobes is 1.0×10^{58} erg (I05). If we adopt the cooling time of the lobes as the integration time of the energy injection into the lobes, we estimated the average kinetic luminosity of 2×10^{45} erg s^{-1}. We note that it is comparable to the typical radiation luminosity of the radio galaxy.

4. SUMMARY

We confirmed the hot ISM and substructures (KF03). Their 'entropy' analysis shows that (1) heating in the galaxy centre ('core'); (2) cooled 'blob' in the north. These results suggest that the lifetime of AGN of 1 Gry. We estimated the average kinetic luminosity in the lifetime of the nucleus.

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