Suzaku Detection of Thermal X-Ray Emission Associated with the Western Radio Lobe of Fornax A

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ABSTRACT

Radio lobes constitute the interface through which AGN jets strongly influence their environments by heating and redistributing the ambient and/or intergalactic gas. Therefore, careful studies of radio lobes are essential for understanding AGN feedback and its impact on the evolution of galaxies and clusters, the details of which are currently under intensive debate. We performed X-ray mapping observations of the Fornax A radio lobe with Suzaku for a total of $\sim$500 ks. By investigating the data covering the entire western lobe, we clearly detected thermal plasma emission with a temperature of $\sim$1 keV in addition to the reported non-thermal emission. The surface brightness is consistent with a spherical distribution peaking at the center of the western lobe with a projected radius of $\sim$12 arcmin (65 kpc). The energy density of the thermal plasma is comparable to or larger than those of magnetic field and non-thermal electrons. If we assume a volume filling factor of unity, the estimated total mass amounts to $10^{10} M_\odot$, which is $\sim$100 times heavier than the central black hole mass and comparable to the current gas mass of the host galaxy. These features give us one of the first evidence that the AGN jet really causes a strong impact on the gas properties in the surroundings.

KEY WORDS: galaxies: individual (Fornax A) — galaxies: magnetic fields — radiation mechanisms: non-thermal — radio continuum: galaxies — X-rays: galaxies

1. Introduction

The co-evolution of galaxies and supermassive black holes (SMBH) is an interesting topic of the cosmology today. Gultekin et al. (2009) presented a plot of the mass of SMBHs and the velocity dispersion of stars, which is a proxy of the bulge mass of the host galaxy. A linear relation is seen between them for various types of galaxies. The SMBHs and bulges have entirely different sizes. For the former, the Schwarzschild radius is $\approx$ 3 mpc, while for the latter, the size is $\approx$ 3 kpc. It is now considered that a galaxy-scale feedback of mass and energy occurs from SMBHs in the form of jets and outflows. We aim to have a quantitative assessment of the feedback.

Radio lobes are a good laboratory for this purpose. They are created by the interaction of ejected mass and the ambient matter and magnetic field. The typical size is several tens of kpc. Lobes are a pair of reservoirs of mass and energy from a SMBH. Therefore, the amount of ejected mass and energy over a long time can be measured quantitatively. However, until recently, observed emission (synchrotron and inverse Compton emission) is generated from non-thermal electrons, which may be only a tiny fraction of the entire mass of the lobe. Detections of thermal emission were awaited.

2. Observations

We chose Fornax A as our target. In figure 1, a 1.5 GHz image by VLA (Fomalont et al. 1989) is shown with a gray scale. The host galaxy NGC 1316 is at the center, and the west and east lobes are on both sides. Fornax A is the second largest lobe in appearance next to Centaurus A. It is also bright and close. It is far from the Fornax cluster center, thus is little contaminated by intra-cluster gas. The extended non-thermal X-ray emission from lobes was first reported using ROSAT and ASCA by Feigelson et al. (1995) and Kaneda et al. (1995) independently. Also, extended thermal X-ray emission was recognized in the X-ray spectra from the lobe, but its distribution and the origin have been unknown (Feigelson et al. 1995, Kaneda et al. 1995, Tashiro et al. 2001,
In order to measure the spatial distribution of the non-thermal and thermal emission in and around the lobe, we conducted XIS mapping for both west and east lobes and a background region with a total of \( \sim 500 \) ks exposure from the Suzaku AO1 through AO8, as shown in figure 1.

3. Results

3.1. Image

Figure 2 shows the obtained mosaic X-ray image in the 0.67–1.5 keV band. The radio intensity is indicated with the blue contours. Extended soft X-ray emission is detected in the lobe. The surface brightness is larger than the tail of the interstellar gas of NGC 1316 (Konami et al. 2010), and the intra-cluster gas of Fornax cluster (Jones et al. 1997).

3.2. Spectrum

Hereafter, we focus on the west lobe, which was observed earlier. We estimated the contaminating X-ray point sources using the XMM-Newton data converging the entire western lobe. XMM-Newton has a much better spatial resolution, hence is more sensitive to point-like sources. We made accumulated spectrum of point sources with XMM-Newton in the pipeline products with a detection significance above \( \sigma \). The spectrum was reproduced well with double power-law model. The surface brightness of the point sources is only \( \sim 1/10 \) of that of the lobe thermal emission at 1 keV. We thus concluded that the ensemble of point-like sources does not account for the observed excess emission in the lobe region.

We accumulated events from the center of the lobe. Figure 3 shows the obtained spectrum. It has excess emission above the Galactic halo and CXB components. When a thermal plasma component was added, the fit improved significantly. In particular, there is a signature of a Ne IX line. Therefore, we concluded that the excess X-ray emission has a thermal origin. The temperature is \( \sim 1 \) keV, but the abundance was unconstrained.

3.3. Spatial Distribution

We made a radial profile of the plasma temperature, X-ray and radio intensity. The plasma temperature is fairly constant within the lobe in figure 4 shows. The Fornax cluster emission is estimated from background region, which is found to be below the observed X-ray intensity in the lobe. The dotted model curves in figure 4 is the PSF-convolved model profile expected from the uniform plasma emission. The spatial distribution of the X-ray intensity is consistent with the uniform thermal plasma distributing within a sphere of a radius of 12'.
thermal model was required to fit the spectrum of both arms of the lobes. There is now accumulating evidence for the presence of ~1 keV thermal extended emission in the lobe or along the jet.

4.2. Estimate of mass and energy
We next estimated the mass and energy of the lobe thermal gas in Fornax A. Assuming a volume filling factor of the thermal plasma to be 1, we derived physical parameters. We compared with Centaurus A by Stawarz et al. (2013). Table 1 shows (1) electron number density, (2) plasma temperature, (3) volume, (4) energy density of the thermal plasma, (5) magnetic field, and (6) non-thermal electrons, and (7) the ratio of thermal and non-thermal energies. We found that the energy density of the thermal plasma is comparable to that of the known non-thermal energy. We also estimated the total mass of the thermal plasma by the product of the proton mass, electron density, and the volume. It is \(~10^{10} M_\odot\). This is 100 times larger than the mass of the SMBH, and 3 times larger than the gas mass of the host galaxy.

4.3. Origin of the lobe plasma
We consider four possibilities for the origin of the observed thermal plasma associated with the lobe.

The first is that the plasma was ejected from the SMBH. However, this is unlikely because the mass of the lobe plasma is much larger than the mass of the SMBH system.

The second is that the gas of the host galaxy was entrained by jet during propagation. This is also unlikely, because the jet immediately becomes non-relativistic and cannot create a large scale structure like lobes.

The third is that the intra-cluster gas was mixed after expansion of the lobe. This is possible, but the Fornax ICM density is too small at the position of Fornax A.

The last is that the swept-up gas of the host galaxy was mixed after expansion of the lobe. This is possible. If this is the case, the mass of the lobe plasma is three times larger than the gas mass of the host galaxy, indicating that the SMBH feedback is large enough to affect the evolution of the host galaxy.

5. Summary
- We have completed the XIS mapping of Fornax A with Suzaku.
- The excess emission above the background emission and the reported non-thermal emission was detected in the lobe.
  - The emission has a thermal origin.
  - The spatial distribution is consistent with an uniform plasma density.
Table 1. Physical parameters of the Fornax A and Centaurus A lobes. The parameters are (1) electron density, (2) temperature, and (3) emitting volume (cm$^3$) assuming a volume filling factor of unity for the lobe thermal emission. The energy densities of (4) the thermal emission, (5) magnetic field, and (6) non-thermal electrons. (7) The ratio of energies in thermal to non-thermal components defined as $\epsilon_T/\epsilon_{mag} + \epsilon_{NT,e}$. The values are from this work and Tashiro et al. (2009). The values are from Stawarz et al. (2013) and Abdo et al. (2010).

<table>
<thead>
<tr>
<th>Object</th>
<th>$n_e$ (cm$^{-3}$)</th>
<th>$k_B T$ (keV)</th>
<th>$V$ (cm$^3$)</th>
<th>$\epsilon_T$ (erg cm$^{-3}$)</th>
<th>$\epsilon_{mag}$ (erg cm$^{-3}$)</th>
<th>$\epsilon_{NT,e}$ (erg cm$^{-3}$)</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>For A$\dagger$</td>
<td>$3.0 \times 10^{-4}$</td>
<td>1.0</td>
<td>$3.4 \times 10^{10}$</td>
<td>$1.4 \times 10^{-12}$</td>
<td>$6.7 \times 10^{-14}$</td>
<td>$5.0 \times 10^{-14}$</td>
<td>2.5</td>
</tr>
<tr>
<td>Cen A$\ddagger$</td>
<td>$0.9-2.5 \times 10^{-4}$</td>
<td>0.5</td>
<td>$2.0 \times 10^{71}$</td>
<td>$2.4 \times 10^{-13}$</td>
<td>$4.0 \times 10^{-14}$</td>
<td>$5.2 \times 10^{-14}$</td>
<td>2.6</td>
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</tbody>
</table>

- Assuming the volume filling factor to be 1,
  - the thermal plasma has an energy density comparable to that of known non-thermal energies.
  - the mass of the lobe plasma is $10^{10} M_\odot$. This is 100 times larger than the mass of the SMBH, and 3 times larger than the gas mass of the host galaxy.

- Similar plasma was found in other lobes (Cen A and M87).

- We speculate that the origin of the lobe plasma is the cluster gas and/or host galaxy gas mixed in the lobe.

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