Discovery of non-thermal X-ray emission from radio lobes of Cygnus A

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Abstract

Using deep *Chandra* ACIS observation data for Cygnus A, we report the detection of non-thermal X-rays from its radio lobes surrounded by a rich intra-cluster medium (ICM). The non-thermal X-ray is considered to be produced via an inverse Compton (IC) process. The spectral energy distribution strongly suggest that the seed photon source of the IC X-rays includes both cosmic microwave background radiation and synchrotron radiation from the lobes. The derived parameters indicate significant energy density of electrons dominance in the Cygnus A lobes under the rich ICM environment.

Key words: galaxies: individual(Cygnus A) — magnetic fields — radiation mechanisms: non-thermal — radio continuum: galaxies — X-ray: galaxies

1. Introduction

Radio lobes in which jets release the kinetic energy originating from active galactic nuclei store enormous amounts of energy as relativistic electrons and magnetic fields. The relativistic electrons in lobes emit synchrotron radiation (SR) in radio and boost seed photons into X-rays and γ-rays via inverse Compton (IC) process. A comparison of the SR and IC fluxes would allow for determining the energy densities u_e and u_m of relativistic electrons and magnetic fields, respectively. So far, the measured IC X-ray flux from the lobes often requires that u_e is considerably greater than u_m (e.g., Tashiro et al. 1998; Isobe et al. 2002). These energies can provide important clues regarding the energy of astrophysical jets and the evolution of radio galaxies.

Cygnus A (Cyg A) is a well-known FR II radio galaxy with an elliptical host. It is a typical object embedded nearly at the center of the galaxy cluster. The radio images show symmetrical double-lobe morphology. The X-ray observations show diffuse X-ray emission, which is considered to be of ICM origin (e.g., Smith et al. 2002), and a cavity corresponding to the radio lobe is also confirmed (e.g., Willson et al. 2006).

In this paper we show a summary of *Chandra* observation of the radio lobe region, though detailed description will be published in a separate paper (Yaji et al. 2009).

2. X-ray observation

Cyg A observation data are obtained from the *Chandra* archive. Cyg A has been observed with an Advanced CCD Imaging Spectrometer (ACIS) detector on eleven occasions. The total exposure of ACIS-I1, ACIS-S3 and ACIS-I3 is 172.2 ks, 47.8 ks and 30.1 ks, respectively. These observations were performed with the default frame time of 3.2 s using the VFAINT format. The purpose of this study is to extract a possible faint and diffuse X-ray emission. Therefore, we added data obtained only by the ACIS-I1 to avoid systematic error by the discrepancy between the energy responses of the CCDs.

3. Results of X-ray analysis

3.1. X-ray image

In figure 1 (*left*), an X-ray source extending towards the vicinity of the nucleus is explained by Smith et al. (2002) as X-ray emission from the ICM of $kT \sim$ 4–9 keV. In figure 1 (*right*), it seems that the X-ray contours formed at 10 and 20 counts per pixel (thin line) avoids the lobe, as if the ICM forms a "Cavity". On the other hand, referring to a dotted circle of $0.75'$ in the radius that is centered at the nucleus, the contours formed at 4 counts per pixel (thick line) shows an extended structure in the direction of the 5 GHz lobe on the east and west side (arrows in the right panel of fig 1). These emission regions seed to be associated with the lobes.

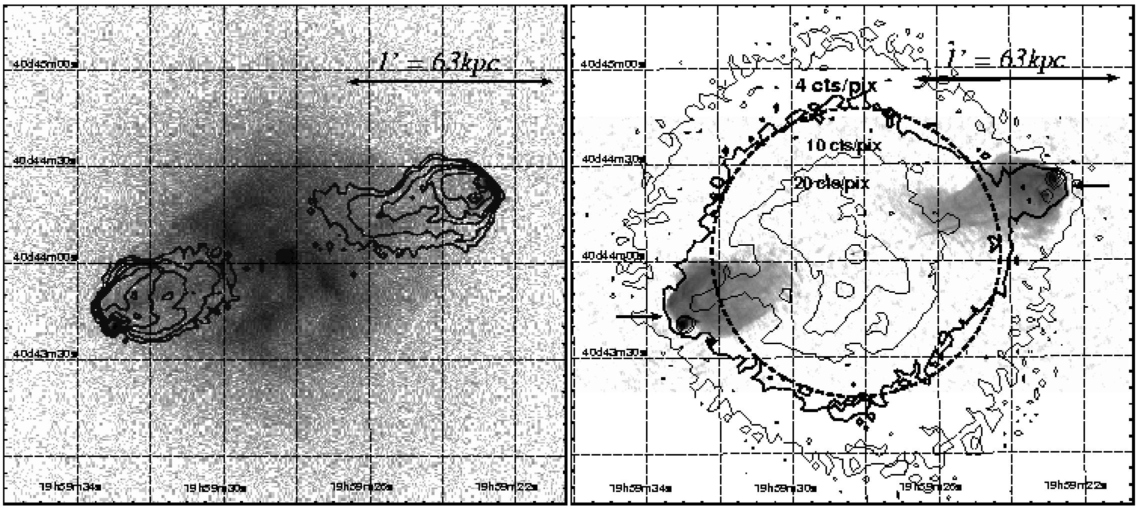

Fig. 1. *Left*: The raw 0.7–7 keV ACIS image of Cyg A comprising co-added data sets from seven ACIS-I1 observations. The white contours represent the radio strength of the 5 GHz band observed by the Very Large Array (VLA), the contours levels are 0.0025, 0.01, 0.03, 0.05, 0.09, 0.2 and 0.5 Jy beam^{-1} for a beam size of 0.36"×0.30". *Right*: ACIS contours image of Cyg A at 0.7–7 keV, superposed on the 5 GHz VLA gray-scale image. Five contours represent an X-ray brightness of 2, 4, 10, 20 and 50 counts per pixel.

3.2. X-ray spectrum of lobe region

In order to evaluate the diffuse X-ray emission associated with the lobes, we accumulated the X-ray spectra from the lobe regions. The lobe spectrum is reproduced not only with a single-temperature Mekal model, such as that of the surrounding ICM component, but also with an additional power-law (PL) model. The X-ray flux densities of PL components for the eastern and the western lobe are derived as 63^{+31}_{-27} nJy and 36^{+31}_{-22} nJy at 1 keV, respectively, and the photon indices are $1.64^{+0.08}_{-0.12}$ and $1.70^{+0.32}_{-0.10}$, respectively.

4. Discussion

In Figure 2, we show the X-ray and radio spectral energy distribution of the eastern and the western lobe of Cyg A. We clearly see that radio spectra do not connect smoothly to the X-ray spectrum, and therefore we conclude that diffuse X-rays are produced via the IC process caused by SR electrons in the lobe. Estimating the seed photons, we consider that energy density of cosmic microwave background ($u_{\rm CMB}$) and that of SR ($u_{\rm SR}$) dominate in the lobe in the following discussion. In order to estimate $u_{\rm e}$ and $u_{\rm m}$ of the lobe, the X-ray and radio data were evaluated with models. We used the SR and synchrotron self-Compton (SSC) model with software developed by Kataoka (2000) and a CMB boosted IC (CMB/IC) component calculated in accordance with Harris & Grindlay (1979). The X-ray data is reproduced by the CMB/IC and the SSC emission. The feature of the emissions from lobes of Cyg A is an effect of the SSC component at the X-ray band. The derived parameters are $u_{\rm e} = 6.0\times10^{-9}$ erg cm^{-3}, $u_{\rm m} = 1.3\times10^{-11}$ erg cm^{-3} in eastern lobe and $u_{\rm e} = 3.4 \times 10^{-9}$ erg cm^{-3}, $u_{\rm m} = 1.6 \times 10^{-11}$ erg cm^{-3} in western lobe. The ratio $u_{\rm e}/u_{\rm m}$ appears to show significant electron dominance in the lobes of Cyg A.

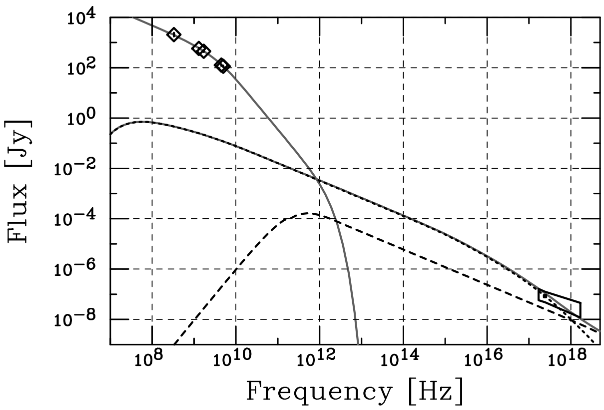

Fig. 2. SED of the eastern lobes of Cygnus A. Squares & ties: X-ray spectrum obtained with *Chandra*. Diamonds: integration flux obtained from radio data. Solid line: synchrotron and IC component. Dash line: CMB/IC component. Dotted line: SSC component.

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