Discovery of an Outstanding Disk in the cD Galaxy of the Hydra A Cluster*

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Abstract

The central cD galaxy of the Hydra A cluster has one of the most powerful active galactic nuclei (AGNs) in the nearby Universe (\(z \lesssim 0.2\)). We report on the discovery of a dust lane in the cD galaxy using Subaru telescope. The \(i’\)-band image shows the existence of a dark band of the size of \(3.6' \times 0.7'\) (4 kpc \(\times 0.8\) kpc), which appears to be quite similar to the dust lane observed in Centaurus A. The morphology indicates that the cold disk that seen as the dust lane is almost edge-on and rotates around the AGN. Since the minor axis of the dust lane is nearly parallel to the radio jets emerging from the AGN, the disk is probably feeding its gas into the central black hole. From the absorption, we estimate the hydrogen column density of the lane is \(N_H = 2.0 \times 10^{21}\) cm\(^{-2}\), and the mass of the disk is \(\sim 8 \times 10^7 M_\odot\). The column density is consistent with constraints obtained from Chandra X-ray observations. The age of the disk is \(\gtrsim 4 \times 10^7\) yr. The position angle of the disk and the galaxy’s photometric axis are misaligned, which may imply that the cold gas in the disk is brought via galaxy mergers. Our observations may indicate that the supply of cold gas by galaxy mergers is required for the most intensive feedback from AGNs.

Key words: galaxies: clusters: individual: Hydra A — galaxies: elliptical and lenticular, cD — galaxies: active — galaxies: ISM — X-rays: galaxies: clusters

1. Introduction

The AGNs in the central cD galaxies of clusters sometimes show violent activities. Such examples are MS 0735.6+7421 (McNamara et al. 2005), Hercules A (Nulsen et al. 2005a), and Hydra A (Nulsen et al. 2005b). In these clusters, clusterscale shock waves have been observed, which indicates that the central AGNs ejected enormous energy (\(\sim 10^{51} - 10^{52}\) erg) in a short time (\(\lesssim 10^8\) yr). The intracluster medium (ICM) of these clusters should have been strongly affected by the AGN activities. It seems that Bondi accretion from hot gas is not sufficient and fueling of cold gas is required for the most powerful feedback from AGNs (McNamara et al. 2011).

The cD galaxy of the Hydra A cluster has been studied by many researchers. It harbors a well known radio source classified as a Fanaroff-Riley type-I (FR-I) source. A pair of jets is ejected from the AGN (3C 218: Taylor et al. 1990), and the huge amount of cosmic-rays contained in the jets may be stably heating the cool core of the cluster (Fujita et al. 2013). The mass of the central supermassive black holes (SMBHs) is estimated to be \(\sim 10^8 M_\odot\) (Fujita & Reiprich 2004; Rafferty et al. 2006). Although the galaxy is an elliptical, star formation activities (\(\lesssim 1 M_\odot\) yr\(^{-1}\)) have been discovered within \(\sim 5\) kpc from the center of the galaxy (McNamara 1995; Cardiel et al. 1998; Wills et al. 2004; Wills et al. 2004; Holt et al. 2007). This may mean that some amount of gas is cooling in the galaxy, although the existence of a massive cooling flow has been denied with the ASCA satellite (Ikebe et al. 1997). Previous observations have indicated that there is a disk-like structure in the galaxy. In the \(U’\)-band, the surface brightness profile is elongated at the galaxy center (McNamara 1995). Observations of optical emission-lines ([O\textsc{iii}], H\(\alpha\), and H\(\beta\)) show that the galaxy has a rotating component with a velocity of \(\sim 300\) km s\(^{-1}\) (Heckman et al. 1985; Melnick et al. 1997). H\(\alpha\) absorption is seen toward the AGN and can be interpreted as a disk (Dwarakanath et al. 1995; Taylor 1996). However, the morphology of the disk has not been well understood. This is mainly because the cluster is relatively distant (\(z = 0.054878\)) and the angular resolution of \(< 1''\) is required to resolve fine structures.

In this letter, we present a Subaru \(i’\)-band image of the cD galaxy of the Hydra A cluster with a superb spatial resolution. We show that the galaxy has a spectacular dust lane. Throughout this letter, we adopt cosmological parameters of \(\Omega_0 = 0.3\), \(\lambda = 0.7\), and \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\). We use
2. Observations and Results

We observed Hydra A with the Prime Focus Camera (Suprime-Cam: Miyazaki et al. 2002) on the Subaru telescope in Hawaii on 2013 January 7. We use the standard pipeline reduction software for Suprime-Cam, SDFRED (Yagi et al. 2002; Ouchi et al. 2004), for flat-fielding, instrumental distortion correction, differential refraction, PSF matching, and sky subtraction and stacking. The seeing was 0.65. The $i$-band image of the cD galaxy is shown in figure 1a. A dust lane (dark band) can be clearly seen in the central region of the cD galaxy. The size of the lane is $3.0 \times 0.7$ (4 kpc $\times$ 0.8 kpc). The position angle of the minor axis is $15^\circ$ from the north to the east. We fit the galaxy image with a Seric profile using GALFIT (Peng et al. 2010), taking PSF size into account. The residual from the best-fits is shown in figure 1b. The position angle of the minor axis of the Seric profile is $40^\circ$, which is close to the result by McNamara (1995) for the $I$-band image ($\sim 55^\circ$), but is not parallel to the minor axis of the disk ($\sim 15^\circ$). This may indicate that the disk formed after the overall structures of the cD galaxy had formed. The extinction is most effective at the center (40%), and it is $A_I = 0.55$. Since the extinction curves of elliptical galaxies are not much different from the one for the Milky Way (Patil et al. 2007), we adopt the Galactic conversion factor ($A_V/A_I = 2.1$: Fitzpatrick 1999) and obtain $A_V = 1.1$ and the column density of $N_H = 2.0 \times 10^{22}$ cm$^{-2}$ from $N_H/A_V = 1.79 \times 10^{21}$ cm$^{-2}$ (Predehl & Schmitt 1995). The value of $N_H$ is almost the same as H I absorption ($N_H = 1.97 \times 10^{21}$ cm$^{-2}$) obtained by Dwarakanath, Owen, and van Gorkom (1995). If the gas is distributed as a uniform disk with a radius of $R \sim 2$ kpc and a height of $H \sim 0.8$ kpc, the disk mass is $M_{\text{disk}} = 8 \times 10^7 M_\odot$. Figure 2 shows the relation of the galaxy to the radio source. A pair of jets emerges with a position angle of $\sim 25^\circ$ and is almost parallel to the minor axis of the dust lane. The jet-dust lane configuration is quite similar to that of Centaurus A.1

3. Discussion

3.1. X-Ray Absorption

We have checked X-ray data obtained with the Chandra X-ray telescope. Hydra A has been observed with Chandra for total 250 ks. Figure 3 shows the exposure-corrected X-ray image of Chandra ACIS-S for 200 ks data in the 0.5–5 keV band. While the central AGN is prominent, the disk-structure is not seen in the figure. X-ray spectral analysis for Chandra ACIS-S and ACIS-I data of the total of 250 ks was performed to constrain an absorption by the disk with response files appropriate for each observation in the 0.4–7.0 keV band.

We study the spectrum of a $4.5 \times 0.5$ region of the disk (region “D” in figure 3). We exclude the nuclear region “N”, because the emission from it can be affected by the absorption in the vicinity of the SMBH. In fact, we find that the absorption associated with the AGN is $N_H = 2.7^{+0.6}_{-0.4} \times 10^{22}$ cm$^{-2}$, which is consistent with the previous result ($N_H = 2.8^{+3.0}_{-1.4} \times 10^{22}$ cm$^{-2}$, Sambruna et al. 2000). Owing to the finite size of pixels (0.5'), the pixels we used actually cover the optical disk ($\sim 3.6 \times 0.7$). First, we extract a spectrum within a $3'$ circle centered on the AGN excluding the AGN and disk.

Fig. 1. (a) $i'$-band image of the cD galaxy of Hydra A. (b) Residual of a fit to the galaxy with a Seric profile.
regions ("N" and "D") in order to estimate the fore- and/or background emissions. The spectrum is represented by two-temperature (cD galaxy + ICM) thermal models (apec) with a common metal abundance multiplied by absorption (phabs): phabs × (apec_{cD} + apec_{ICM}). The results are $kT = 1.0^{+0.2}_{-0.2}$ and $3.5^{+0.3}_{-0.2}$ keV with 0.7 ± 0.2 solar abundance, and $N_H = 3.3^{+1.2}_{-1.1} \times 10^{20}$ cm$^{-2}$ (errors of 90% confidence). The absorption value is almost consistent with the Galactic absorption ($N_H = 4.68 \times 10^{20}$ cm$^{-2}$, Kalberla et al. 2005) in the direction of Hydra A. Fixing these fore- and/or background parameters, we investigate the upper limit of the absorption by the disk. Here, we assume that the emission from the disk region is represented by two-temperature thermal models (cD galaxy + ICM) and only the cooler component (cD galaxy) is absorbed by the disk: phabs × (phabs$_{disk} \times$ apec$_{cD}$ + apec$_{ICM}$). We employ an increment of $\delta \chi^2 = 2.706$ as the measure for the 90% upper limit of the absorption. We find that the upper limit is $N_H = 3.1 \times 10^{21}$ cm$^{-2}$, which is consistent with the disk absorption of $N_H = 2.0 \times 10^{21}$ cm$^{-2}$ (section 2). Note that the absorption by the dust lane on the both sides of the AGN should be smaller than that in the direction of the AGN (region "N").

3.2. Nature of the Disk

Optical emission-lines have been discovered from the cD galaxy of Hydra A. If the rotation of the emission-line component corresponds to that of the dust lane, the rotation velocity is $v_{rot} \sim 300$ km s$^{-1}$ (Heckman et al. 1985; Melnick et al. 1997), which gives the rotation period of $T_{rot} = 2 \pi R / v_{rot} \sim 4 \times 10^7$ yr. The age of the cold disk should be larger than this period. From the observations of a shock wave in the ICM, Nulsen et al. (2005b) indicated that there was a strong outburst of the AGN with an energy of $\sim 10^{51}$ erg $\sim 1.4 \times 10^8$ yr ago. This outburst may be related to the formation of the disk. Note that if all the disk gas at present ($M_{disk} = 8 \times 10^7 M_\odot$) flowed into the SMBH, energy comparable to the previous outburst might be released ($\sim 0.1 M_{disk} c^2 \sim 10^{51}$ erg).

The angular distance between the X-ray AGN and the center line of the dust lane is $\Delta \theta \lesssim 0.5$ or $dl \lesssim 0.55$ kpc (figure 3). If the AGN is located at the center of the disk, the inclination angle of the disk is $dl / R \lesssim 16^\circ$, and the disk is almost edge-on. This may also mean that the jets from the AGN are almost on the plane of the sky at present. On the other hand, the positions of pairs of outer lobes show that the jets were not being injected on the plane of the sky and were oriented $\sim 40^\circ$ about the plane in the past (Wise et al. 2007). The change of the jet direction may be caused by precession (Taylor et al. 1990).

3.3. Origin of the Dust Lane

The cD galaxy is a harsh environment for dust. In the presence of the hot ICM of $\sim 10^7$ K, collision with hot particles destroys the dust. The destruction time is

$$\tau_d = 2.4 \times 10^5 \left( \frac{n_e}{1 \times 10^3 \text{ cm}^{-3}} \right) \left( \frac{a}{0.1 \mu \text{m}} \right) \text{ yr},$$

where $n_e$ is the ICM density and $a$ is the radius of dust grains (Draine & Salpeter 1979; Patil et al. 2007). If we adopt $n_e = 0.05$ (Nulsen et al. 2005b) and $a = 0.1 \mu \text{m}$, the destruction time is $\tau_d = 4.8 \times 10^6$ yr. The mass loss rate from evolved stars in the galaxy is

$$M_s \approx 6 \times 10^{-6} \left( \frac{D}{\text{Mpc}} \right)^2 \left( \frac{S_{12} - 0.042 S_{100}}{\text{mJy}} \right) M_\odot \text{ yr}^{-1},$$

where $D$ is the distance to the galaxy, and $S_x$ is the flux at $x \mu \text{m}$ (Knapp et al. 1992). For Hydra A, the luminosity distance is $D = 245$ Mpc, and the flux is $S_{12} = 5$ mJy (Donahue et al. 2011). Since we are interested in the upper limit of the dust mass $M_d$ and since we avoid the complications caused by the...
difference of apertures at different wave lengths, we assume that \( S_{100} = 0 \). For these values, we obtain \( M_\star = 2 \ M_\odot \) yr\(^{-1}\). Assuming that the gas-to-dust ratio is \( f = 100 \), the rate of accumulation of dust is

\[
\frac{dM_\text{d}(t)}{dt} = \frac{M_\star}{f} - \frac{M_\text{d}(t)}{\tau_\text{d}}
\]

(3)

(Patil et al. 2007). This equation can be solved easily; \( M_\text{d} \)
approaches its final value \( M_{\text{d,0}} = 9.5 \times 10^4 M_\odot \) in a time-scale of a few \( \tau_\text{d} \). Since \( M_{\text{d,0}} < M_{\text{d,final}}/f \), this may indicate that the dust is externally provided in the galaxy.

If the dust is not provided internally, the dust may be brought by merged galaxies. That is the case for Centaurus A (Espada et al. 2012). The misalignment between the disk and the galaxy’s photometric axis (section 2) is favorable to the merger scenario. Based on a semi-analytic model, Fujita, Nagashima, and Gouda (2000) indicated that the fraction of cD galaxies that have cold gas brought through galaxy mergers induced by dynamical friction is small. However, their criterion for existence of cold gas in a cD galaxy is \( 10^8 M_\odot \), and thus more cD galaxies should have cold gas of \(< 10^8 M_\odot \) (see Tutukov et al. 2007). Alternatively, a complicated solution may be required. For example, while dust provided by evolved stars in a cD galaxy is shielded from the surrounding hot gas (Donahue et al. 2011), it is mixed with cold gas provided by a weak cooling flow (Gasperi et al. 2012).

3.4. Comparison with Other cD Galaxies

Among cD galaxies with outstanding dust lanes and disks, those of Cygnus A and Hydra A are known for having extremely active radio sources (Kino & Kawakatu 2005; McNamara et al. 2005a). The cD galaxy of Cygnus A has a well-developed cold disk rotating around the AGN and the minor axis of the disk is parallel to the jets like Hydra A (Jackson et al. 1998; Young et al. 2002). On the other hand, the cD galaxy of Hercules A does not have a disk-structure, although it has prominent twin jets (O’Dea et al. 2013). This may be because the cold disk has disappeared by now, while it caused the strong outburst in the past. Note that in some non-cD radio galaxies, dust lanes that resemble the one we found in Hydra A have been observed (de Koff et al. 2000; de Ruiter et al. 2002).

4. Conclusions

We observed the cD galaxy of the Hydra A cluster with Subaru telescope and found an outstanding dust lane. The disk seen as the dust lane is edge-on and the minor axis is parallel to radio jets, but it is not parallel to the minor axis of the host galaxy. The disk mass and the rotation period are \( 8 \times 10^7 M_\odot \) and \( \sim 4 \times 10^7 \) yr, respectively. The column density of the dust lane \( (N_{\text{H}} = 2.0 \times 10^{21} \text{ cm}^{-2}) \) is consistent with the constraints obtained by X-ray observations. Our results may indicate that galaxy mergers and the supply of cold gas to the SMBHs is essential to the most powerful activities of the AGNs.

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