X-ray study of the double source plane gravitational lens system Eye of Horus observed with XMM-Newton

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ABSTRACT

A double source plane (DSP) system is a precious probe for the density profile of distant galaxies and cosmological parameters. However, these measurements could be affected by the surrounding environment of the lens galaxy. Thus, it is important to evaluate the cluster-scale mass for detailed mass modeling. We observed the Eye of Horus, a DSP system discovered by the Subaru HSC–SSP, with XMM–Newton. We detected two X-ray extended emissions, originating from two clusters, one centered at the Eye of Horus, and the other located ~100 arcsec northeast to the Eye of Horus. We determined the dynamical mass assuming hydrostatic equilibrium, and evaluated their contributions to the lens mass interior of the Einstein radius. The contribution of the former cluster is $(1.1^{+1.1}_{-0.8} \times 10^{12})\ M_{\odot}$, which is $21 - 76\%$ of the total mass within the Einstein radius. The discrepancy is likely due to the complex gravitational structure along the line of sight. On the other hand, the contribution of the latter cluster is only $\sim 2\%$ on the Eye of Horus. Therefore, the influence associated with this cluster can be ignored.

Key words: galaxies: clusters: individual: HSC J142449-005322 – gravitational lensing: strong – galaxies: clusters: intracluster medium
1 INTRODUCTION

The Eye of Horus is a strong gravitational lens object (Tanaka et al. 2016) that was discovered by the Subaru HSC-SSP survey (HSC-SSP; Aihara et al. 2018b,a; Miyazaki et al. 2018; Komiyama et al. 2018; Kawanomoto et al. 2018; Furusawa et al. 2018; Bosch et al. 2018; Huang et al. 2018;Coupon et al. 2018). It is known as a precious double source plane (DSP) object. The lens galaxy of the Eye of Horus is a massive (stellar mass $\sim 7 \times 10^{11} M_{\odot}$) early-type galaxy which is located at (RA, DEC) = $(14^h 24^m 49^s.0, -00^\circ 53' 21.5'' )$ (J2000), and the redshift of the lens galaxy is $z = 0.795$. Since there are two background galaxies behind the lens galaxy whose redshifts are $z = 1.302$ and 1.988, respectively, an Einstein ring and an arc corresponding to these background galaxies are projected near the Einstein radii.

DSP system is a precious probe for the gravitational structure of lens galaxies and cosmological parameters. In a distant galaxy at $z \sim 0.8$, it is usually difficult to determine the gravitational structure inside the galaxy using only the stellar distribution. However, when a lens galaxy has a double source lens image, the gravitational structure at 10–100 kpc can be determined by combining lensing and dynamics, even if it is located at $z \sim 0.8$ (e.g., Sonnenfeld et al. 2012). The matter density parameter $\Omega_M$, the equation of state parameter $\omega$, and the Hubble parameter by cosmic microwave background (CMB) measurements (Komatsu et al. 2011) degenerate. On the other hand, measurements of the ratio of two Einstein radii in a DSP object enables us to break the degeneracy between the Hubble parameter and the other two parameters (Collett et al. 2012; Collett & Auger 2014; Linder 2016).

The above constraints are obtained with high accuracy if the lens galaxy is an isolated system. However, Keeton & Zabludoff (2004) suggested that if it lies in a group or a cluster of galaxies, the lens image would be affected by the environment surrounding the lens galaxy, depending on the distance between lens galaxy and the group/cluster center. The lens galaxy of the Eye of Horus corresponds to the brightest cluster galaxy (BCG) of HSC J142449-005322 (hereafter the main cluster) in the CAMIRA cluster catalog (Oguri et al. 2018). The richness of this cluster is $N_{gal} \sim 34$, and its redshift is $z \sim 0.801$. However, BCGs identified by optical data are known to often deviate from the cluster center up to several hundred kpc (Oguri et al. 2018). Therefore, we should determine the cluster center position accurately using X-ray data. Furthermore, Oguri et al. (2018) suggested that there is another cluster (HSC J142456-005157, hereafter the north-east (NE) cluster) located at (RA, DEC) = $(14^h 24^m 56^s.4, -00^\circ 51' 57.3'' )$ (J2000). The richness is $N_{gal} \sim 37$, and its redshift is $z \sim 0.768$. These two clusters are separated only by ~2$, and photometric data suggests that the difference of the redshifts is only $\Delta z \sim 0.03$, so the gravitational potential of the NE cluster may affect the lens image. If these two clusters are a merger, the lens model of the Eye of Horus may be complicated.

X-ray observations provide us with crucial information on the cluster-scale environment. We observed X-ray emission surrounding the Eye of Horus with XMM–Newton and report the results in this paper. Two extended emissions were detected at the position of these two clusters ($\S$2).

We fitted the X-ray image to determine the center position and the extension of the intracluster medium (ICM) of each cluster ($\S$3). We fitted their spectra to determine the temperature of the ICM ($\S$4). We calculated the cluster mass assuming hydrostatic equilibrium (hereafter hydrostatic mass), based on the parameters obtained by image fitting and spectral fitting, and we evaluated the effect of the cluster-scale dynamical mass on the lens potential ($\S$6).

Throughout this paper, we adopt a Hubble constant of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, and cosmological density parameters of $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$. 1$''$ corresponds to 7.64 kpc at the main cluster and 7.52 kpc at the NE cluster, respectively. The solar abundance table by Lodders & Palme (2009) is used. All error ranges are 68% confidence intervals unless otherwise stated.

2 OBSERVATION AND DATA REDUCTION

The Eye of Horus was observed with XMM-Newton on 2018 January 6. Table 1 shows detail information on the observation. The medium filter for MOS (Turner et al. 2001) and the thin filter for pn (Strüder et al. 2001) were selected, respectively. We used SAS version 17.0.0 to extract images and spectra, and CCF version XMM-CCF-REL-356 as a calibration database. We used the data analysis pipeline of Miyakoda et al. (2018) to adopt the standard data reduction. Raw data were filtered with the standard method and the events that matched the conditions of $\text{FLAG} = 0$ and $\text{PATTERN} \leq 12$ for MOS, and $\text{FLAG} = 0$ and $\text{PATTERN} \leq 4$ for pn were extracted. Bright point sources were excluded by using cheese command.

Fig. 1 shows a composite image of MOS1, 2 and pn in the 0.4–2.3 keV band. In addition to the main cluster and the NE cluster, a couple of sources were detected. There are two very bright point sources, ~1$''$ and ~2$''$ northwest of the main cluster (hereafter NW PS and far NW PS). There are two faint point sources, ~30$''$ east of the main cluster and ~1$''$ south-southeast of the NE cluster, respectively (hereafter the 2nd-peak and the 3rd-peak).

3 IMAGING ANALYSIS

We fitted the X-ray image to determine the center coordinates of the main cluster and the NE cluster. A fitting area of 315$''$ square, roughly centered at the main cluster, was selected to evaluate background properly as shown in Fig. 1. The NW PS and the far NW PS are brighter than the main cluster, so the circular regions with a radius of 30$''$ centered at the point sources were excluded.

We used Sherpa (Freeman et al. 2001) in CIAO version 4.10 (Fruscione et al. 2006) for image fitting. The source distribution models were convolved with the PSF model and the exposure maps. The PSF maps were generated at the energy of 1.35 keV and at the on-axis position using psfgen tool. The images, the PSF maps, and the exposure maps were rebinned so that the pixel size becomes 5$''$. The three images were fitted simultaneously using the C statistic (Cash 1979).

We adopted a 2-dimensional single-$\beta$ model for the main cluster, a 2-dimensional double-$\beta$ model for the NE cluster,
Table 1. Observation log. The flare time is removed from the exposure time.

| Target name       | Obs ID   | Start time [UT] | Exposure time (MOS1 / MOS2 / pn) [ks] | RA       | Dec       |
|-------------------|----------|-----------------|---------------------------------------|----------|-----------|
| HSC J142449-0053  | 0800790101| 2018-01-06 06:26:13 | 43.4 / 44.5 / 30.0                      | 14:24:49.0 | -00:53:21.6|

Figure 1. X-ray surface brightness distribution near the Eye of Horus. It is a merged image of MOS1, 2 and pn in the 0.4–2.3 keV band, after subtracting the non-X-ray background (NXB), correcting exposure-time, and smoothing with $\sigma = 5\arcsec$. The green lines show the region for image fitting. The green and the blue cross points show the best-fit center positions of each source obtained from image fitting.

Figure 2. X-ray contours generated from Fig. 1, superposed on the optical image observed with Subaru–HSC. Green crosses show the best-fit center positions of the main cluster, the NE cluster, the 2nd peak, and the 3rd peak.

The main cluster. But the center position determined from image fit is $3.8 \pm 1.0\arcsec$ shifted to the south from the center of the Eye of Horus. On the other hand, the best-fit position of the NE cluster deviated considerably (~40″) from the optically selected BCG (see Fig. 2), which is probably due to an error of optical identification, since CAMIRA cluster finding algorithm has a certain uncertainty in the determination of the BCG. There is an elliptical galaxy SDSS J142454.68–005226.3, $3.8 \pm 0.5\arcsec$ northwest of the X-ray peak of the NE cluster, and we infer that this object is the correct BCG of the NE cluster. The X-ray peak of the main cluster and the NE cluster shifted $3.8\pm1.0\arcsec$ south and $3.8\pm0.5\arcsec$ southeast from the optical counterpart, respectively. These discrepancies are higher than the position uncertainty of the EPIC, which is $1.2\arcsec$ ($1\sigma$) according to XMM-Newton Calibration Technical Notes v3.11, and we infer that these discrepancies are caused by the cluster-scale structure.

We investigated whether the main cluster and the NE cluster are a merger. Fig. 3 shows a contour map of the galaxy probability density distribution in the redshift band of each cluster generated by MIZUKI (Tanaka 2015), overlaid with the X-ray image. MIZUKI determines the probability density distribution of the galaxies at any redshift from the photometric data. From the left panel, in the redshift band of the NE cluster, the galaxy density is relatively low.
Table 2. Best-fit parameters obtained from the image fitting.

| Parameter             | Main cluster | NE cluster inner | NE cluster outer | 2nd-peak | 3rd-peak | Background |
|-----------------------|--------------|------------------|------------------|----------|----------|------------|
| $r_c$ [arcsec / kpc]  | $21.5^{+4.1}_{-1.9}$ / $194^{+71}_{-45}$ | $2.27^{+0.62}_{-0.16}$ / $17.1^{+4.7}_{-1.2}$ | $60.0^{+9.7}_{-5.6}$ / $451^{+73}_{-42}$ | -        | -        | -          |
| $\beta$               | $0.67^{+0.08}_{-0.03}$ | $0.78^{+0.14}_{-0.06}$ | -                | -        | -        | -          |
| RA [deg]              | $216.2038^{+0.00030}_{-0.00029}$ | $216.22837^{+0.00012}_{-0.00011}$ | $216.21185^{+0.00108}_{-0.00011}$ | $216.23378^{+0.00136}_{-0.00002}$ | -        | -          |
| DEC [deg]             | $-0.89034^{+0.00027}_{-0.00029}$ | $-0.87489^{+0.00014}_{-0.00016}$ | $-0.89053^{+0.00014}_{-0.00006}$ | $-0.89204^{+0.00039}_{-0.00050}$ | -        | -          |
| norm MOS1 [cnt/s/deg$^2$] | $11.6^{+0.7}_{-0.4}$ | $518^{+66}_{-167}$ | $2.0 \pm 0.3$ | $82 \pm 16$ | $59 \pm 10$ | $0.60 \pm 0.03$ |
| norm MOS2 [cnt/s/deg$^2$] | $13.3^{+0.8}_{-0.5}$ | $= \text{norm(MOS2, main cluster)} \times \text{norm(MOS1, each component)} / \text{norm(MOS1, main cluster)}$ | - | - | - |
| norm pn [cnt/s/deg$^2$] | $12.7^{+0.8}_{-0.5}$ | $= \text{norm(pn, main cluster)} \times \text{norm(MOS1, each component)} / \text{norm(MOS1, main cluster)}$ | - | - | - |

C-statistic 16011
d.o.f. 11208
C-statistic/d.o.f. 1.429

Figure 4. The X-ray surface brightness profile between the main cluster and the NE cluster (black: MOS1, red: MOS2, green: pn). The top panels show extracted regions of X-ray surface brightness. The dashed, dotted, dash-dotted, dot-dot-dashed, dash-dash-dotted lines correspond to the main cluster, the NE cluster outer, the NE cluster inner, the 2nd-peak, the background components of the best-fit model, respectively, and the solid line shows the sum of them.

4 SPECTRAL ANALYSIS

We fitted the EPIC spectra to determine the ICM temperatures of the two clusters. Fig. 5 shows the definition of the spectral integration regions. From the imaging analysis, we found that the intensity of cluster emission reaches the background level at the radius of $\sim 100''$ (764 and 752 kpc for the main and the NE cluster, respectively). Therefore, with a margin, let the radius $2''$ be the boundary between each cluster region and the background region. Since the main cluster and the NE cluster are separated only by $\sim 100''$, we divided the regions of the main cluster and the NE cluster at the midpoint between them. The background region was defined as a circle of a radius of $8'$ centered at the midpoint,
The NE cluster region was divided into the inner region excluding the main cluster and the NE cluster regions. Note that, the NE cluster region was divided into the inner region \((r \leq r')\) and the outer region \((r' < r \leq 2r')\) to consider temperature gradient because the X-ray emission of the NE cluster is concentrated in the central region. There are many point sources in these regions. Bright point sources were removed by the \texttt{cheese} command. Faint point sources that can be distinguished by eye, but cannot be removed by \texttt{cheese} command were manually removed. Table 3 summarizes photon counts of the four regions.

Table 3. Photon counts in the four regions. The energy bands are 0.3–11 keV for the MOS spectra and 0.4–11 keV for the pn spectra, respectively. The net count means the QPB-subtracted count.

| Region         | Instrument | Counts | Net counts |
|----------------|------------|--------|------------|
| Main cluster   | MOS1       | 1683   | 1129.1     |
|                | MOS2       | 1678   | 1115.3     |
|                | pn         | 3560   | 2022.9     |
| NE cluster inner | MOS1       | 685    | 571.3      |
|                | MOS2       | 725    | 577.7      |
|                | pn         | 1692   | 1297.3     |
| NE cluster outer | MOS1       | 932    | 490.5      |
|                | MOS2       | 804    | 494.1      |
|                | pn         | 1183   | 815.4      |
| Background     | MOS1       | 17059  | 7703.5     |
|                | MOS2       | 21771  | 8985.0     |
|                | pn         | 41210  | 19698.7    |

Quiescent particle background (QPB) spectra were generated using \texttt{mos-spectra} and \texttt{pn-spectra} and subtracted from the spectra of the four regions. Then the spectra were rebinned so that each bin contained at least 20 counts. The energy band was set to 0.3–11.0 keV for MOS and 0.4–11.0 keV for pn.

We used XSPEC version 12.10.1 (Arnaud 1996) for spectral fitting. We adopted the APEC version 3.0.9 (Smith et al. 2001) as an optically thin thermal plasma model. We adopted \texttt{phabs} as a photoelectric absorption model, and the column density was fixed at 3.25x10^{20} cm^{-2} based on the LAB survey (Kalberla et al. 2005). EPIC spectra have many background components (De Luca & Molendi 2004; Kunz & Snowden 2008; Freyberg et al. 2004; Snowden et al. 2004; Carter & Sembay 2008). We fitted all the spectra of the detectors and the four regions simultaneously following Snowden et al. (2008).

Emission of each cluster was represented by \texttt{phabs*apec}, and the parameters were linked among detectors. The redshift of each cluster was fixed at the value derived from photometric data (Oguri et al. 2018). The abundances of the NE cluster component in the inner and the outer regions were linked with each other. The projection effects are considered, assuming that each source is spherically symmetric with constant density.

The response files were created by SAS tools. RMFs were generated together with spectra using \texttt{mos-spectra} and \texttt{pn-spectra} tools. We adopted extended source ARFs that were generated using \texttt{arfgen} tool. We adopted \(\chi^2\) statistic to the statistical test.

Fig. 6 and Table 4 show the best-fit parameters of the spectral fitting. From Table 4, the temperature of the NE cluster has radial dependence although it is marginal. We also tested whether there is a temperature gradient in the main cluster, by dividing the region of the main cluster into two, an inner circle of \(1'\) radius and an annulus of \(2'\) radius and an annulus of \(2'\) radius and an annulus of \(2'\) radius and an annulus of \(2'\) radius, but we could not find the difference in the temperature between the two regions \((kT_{\text{in}} = 5.6_{-0.7}^{+0.8} \text{ keV}, kT_{\text{out}} = 5.9_{-0.8}^{+0.7} \text{ keV})\). When the redshifts were made free, they became unacceptably high \((z_{\text{main}} = 2.7_{-0.13}^{+0.08}, z_{\text{NE}} = 3.7_{-0.12}^{+0.24})\). Note that, since the instrumental Al K\(\alpha\) and Si K\(\alpha\) lines are predominant in the 1.3–1.9 keV range in MOS spectra and in the 1.3–1.6 keV range in pn spectra (see Fig 6), we evaluated the influence of these lines to the fitting result by excluding these energy ranges. The parameters of the ICM unchanged within the error ranges of Table 4.

From the result of image fitting and spectral fitting, the surface brightness distribution of the NE cluster is well represented by a double-\(\beta\) model, and the spectrum is represented by a two-temperature model. These results suggest...
that the NE cluster is divided into two components, the inner component ($r_c = 2.44^{+0.60}_{-0.16}$ arcsec, $kT = 3.36^{+0.47}_{-0.40}$ keV) and outer component ($r_c = 57.8^{+5.1}_{-5.5}$ arcsec, $kT = 0.94^{+0.82}_{-0.32}$ keV), and the gravitational potential of the NE cluster is concentrated in the central elliptical galaxy.

5 DISCUSSION

5.1 Mass of the clusters

Based on the distributions and the temperatures of the ICM obtained by the results of the image fitting and the spectral fitting, we calculated the hydrostatic mass of the main cluster and the NE cluster, and evaluated the effect of the cluster-scale environment on the lens image of the Eye of Horus. When the ICM is in hydrostatic equilibrium and its surface brightness distribution follows a $\beta$-model, the hydrostatic mass density at a radius $r$ from the cluster center can be represented as follows (Ota et al. 1998)

$$\rho(r) = \frac{1}{4\pi r^2} \left( \frac{3k_B T \beta}{Gm} \right) \left( \frac{3r^2}{r^2 + r_c^2} - \frac{2r^4}{(r^2 + r_c^2)^2} \right)$$

(1)

where $k_B$, $\beta$, and $G$ are the Boltzmann constant, the average ion mass, and the gravitational constant, respectively. From this equation, the hydrostatic mass which are projected on the sky plane within a radius $r$ is given by

$$M(r) = \frac{3k_B T \beta \pi}{Gm} \cdot \frac{r^2}{r^2 + r_c^2}$$

(2)

$r_{200}$ ($r_{500}$) is defined as the radius within which the average density is 200 (500) times the critical density, and $M_{200}$ ($M_{500}$) is the hydrostatic mass within $r_{200}$ ($r_{500}$), i.e.,

$$M_{200} = M(r_{200}) = 200 \cdot \frac{3H^2}{8\pi G} \cdot \frac{4\pi}{3} \cdot r_{200}^3$$

(3)

and

$$M_{500} = M(r_{500}) = 500 \cdot \frac{3H^2}{8\pi G} \cdot \frac{4\pi}{3} \cdot r_{500}^3$$

(4)

where $H$ is the Hubble parameter, $H = 106$ km s$^{-1}$ Mpc$^{-1}$ for the main cluster and $H = 104$ km s$^{-1}$ Mpc$^{-1}$ for the NE cluster, respectively. Using equations (2) and (3) or (4), $r_{200}$ and $M_{200}$, or $r_{500}$ and $M_{500}$, can be determined. Since the NE cluster has two components, when we use equation (2) for the NE cluster, we combined the inner component and the outer component with their density ratio.

Table 5 shows $M_{200}$, $M_{500}$, and $r_{200}$, $r_{500}$ thus obtained. We confirmed that there are two massive cluster, $5.6^{+1.3}_{-0.8} \times 10^{14}$ $M_\odot$ and $2.7^{+0.5}_{-0.3} \times 10^{14}$ $M_\odot$, respectively, in the field of the Eye of Horus. The cluster mass inferred from the mass-richness scaling relation (Okabe et al. 2018) is also shown in Table 6 for comparison. The two clusters have comparable optical mass, while the hydrostatic mass of the main cluster estimated by the X-ray data is almost three times larger than that obtained from the mass-richness relation. This is probably because measurement of the number of the member galaxies has large uncertainty in the distant cluster, and we assumed spherical symmetry and extrapolated the isothermal single-$\beta$ model to the outside where X-ray emission cannot be seen.

5.2 Mass within the Einstein radius

The total mass $M_{\text{tot}}$ projected on the sky plane within the Einstein radius can be calculated from the Einstein radius of the lens galaxy, and angular diameter distances to the lens galaxy, to the background source, and between the lens.
galaxy and the background source. The Eye of Horus has two background galaxies (S1 and S2 in Tanaka et al. 2016) and Einstein radii. The Einstein radius of S2 is affected not only by the lens galaxy but also by S1 since S2 is located behind S1. Therefore, in this paper, we only used S1. Since the Einstein radius of the S1 is $2.14 \pm 0.02$ arcsec (Sonnentfeld et al. 2019), $M_{\text{tot}}$ is $(2.98 \pm 0.04) \times 10^{12} M_\odot$, which is $4.5$ times the stellar mass of the lens galaxy $(6.6^{+0.7}_{-0.4} \times 10^{11} M_\odot$, Tanaka et al. 2016).

Using equation (1), we calculated $M_E$, the mass of each cluster projected on the sky plane within the Einstein radius of the lens galaxy, which is summarized in Table 7. In calculating $M_E$ for each cluster, we extrapolated the result of the image and spectral fitting to a sufficiently distant point along the line of sight where the mass calculation converges, although the X-ray emission can be seen only up to $\sim r_{500}$. Note that, we considered a statistical error ($1.0\%$) and XMM position uncertainty ($1.2\%$) as a position error.

$M_E$ of the main cluster is $1.1^{+0.7}_{-0.4} \times 10^{12} M_\odot$, which is larger than the stellar mass of the lens galaxy, yet explains only $25-60\%$ of $M_{\text{tot}}$. Therefore, we investigated the cause of the discrepancy. First, we tested an NFW density profile (Navarro et al. 1996) for the mass estimation because it has steeper and deeper potential at the central region than that of a single-$\beta$ model. We used relation between the scale radius of the NFW density profile $r_s$ and the core radius of the $\beta$ model $r_c$, $r_c = r_s / 0.22$ (Makino et al. 1998). Then, we calculated $M_E$ in the same manner and obtained $M_E_{\text{NFW}} = 1.1^{+1.2}_{-0.5} \times 10^{12} M_\odot$. The upper limit is higher than the mass derived from the $\beta$ model. However, the mass discrepancy cannot be explained even if only the NFW density profile is adopted. Therefore, we conclude that $M_E_{\text{NFW}} = 1.1^{+1.2}_{-0.5} \times 10^{12} M_\odot$ is a secure limit of the mass related to the main cluster, and it can explain $21-76\%$ of $M_{\text{tot}}$ as long as we estimate one-component gravitational potential. Note that, there is a possibility that the gravitational potential of the central lens galaxy was not measured properly since we used a single-$\beta$ model. To evaluate the influence of the central lens galaxy, we tested to fit the X-ray surface brightness of the main cluster with a double-$\beta$ model. Then we calculated $M_E$ by stacking the components of the inner and the outer in the density ratio. However, we could not determine the mass since the normalization of the inner component has a large error ($M_E_{\text{2p}} = 3.3^{+14.4}_{-2.4} \times 10^{12} M_\odot$). We did not consider the radial dependence of the temperature for the main cluster, but the Einstein ring is much smaller than the core radius of the main cluster (25.0$''$), and is located completely within it. And the ICM of the main cluster is well represented by a one-temperature model. Therefore, the influence of the radial dependence of the temperature is expected to be small.

Several studies reported that the hydrostatic mass is underestimated compared to $M_{\text{tot}}$ derived from the strong lens data. Ota et al. (2004) reported that the hydrostatic mass of the strong lens cluster CL 0024+17 is smaller by a factor of 2–3. They discussed possibilities that there are additional mass components since the lens cluster is a line of sight merger, or that there are substructures in the central region of the lens cluster, and the mass profile follows the NFW density profile rather than the $\beta$ model. Fig. 3 indicates that the main cluster has complex galaxy distribution along the line of sight of the Eye of Horus. There might be complex mass structures which are not considered in our analysis. To evaluate the degree of anisotropy of the mass distribution, we divided the area into the sectors of an opening angle of $90^\circ$ in the NE, NW, SW and SE quadrants, and fitted the surface brightness distribution of each sector with a single-$\beta$ model. However, since there are not enough photon counts, we could not find any significant difference in each parameter. Hashimoto et al. (1999) systematically studied 50 strong lens clusters and classified them into two types, one has the X-ray peak and the strong lens galaxy at the same center position, and the other at the different positions. He reported that the former and the latter follow $M_{\text{tot}}/M_E = 2.17 \pm 0.13$ and $M_{\text{tot}}/M_E = 3.33 \pm 0.39$, respectively. Since the X-ray peak of the main cluster is slightly shifted from the center of the lens galaxy, the Eye of Horus may follow the latter.

On the other hand, $M_E$ of the NE cluster is only $\sim 2\%$ of the $M_{\text{tot}}$. This is probably because the gravitational potential of the NE cluster is concentrated in the central elliptical galaxy. Note that, however, several studies reported that the mass of the cluster whose center position is located far from the lens galaxy could affect the shape of lens image as external shear (e.g., Grillo et al. 2008). This effect needs to be considered in the detailed lens modeling of the Eye of Horus in future studies.
6 CONCLUSIONS

We observed X-ray emission around the Eye of Horus with XMM-Newton to evaluate the influence of cluster-scale mass structure on the lens image of the Eye of Horus. There are two clusters, the main cluster and the NE cluster which is located ∼100′ northeaster of the lens galaxy, and we found that the center position of the main cluster is located 3.8 ± 1.0′ south of the lens galaxy. The surface brightness distribution of the main cluster and the NE cluster is represented by a single, and a double β model, respectively. We also revealed that the spectrum of the main cluster is represented by a one-temperature model, while that of the NE cluster needs a two-temperature model.

The total mass projected on the sky plane within the Einstein radius \( M_{\text{E}} \) determined by the Einstein radius is \( \sim 3.0 \times 10^{12} M_\odot \), which is \( \sim 4.5 \) times larger than the stellar mass of the lens galaxy. We calculated the hydrostatic mass projected on the sky plane within the Einstein radius of the lens galaxy, \( M_{\text{E}} \), using the X-ray data. \( M_{\text{E}} \) of the NE cluster is \( 6.1_{-4.9}^{+1.4} \times 10^{10} M_\odot \), which is only \( \sim 2\% \) of \( M_{\text{E}} \). Therefore, the influence of \( M_{\text{E}} \) is small. On the other hand, \( M_{\text{E}} \) of the main cluster is \( 1.1_{-0.1}^{+0.7} \times 10^{13} M_\odot \), which explains only 25–60\% of \( M_{\text{E}} \). We tested an NFW density profile instead of the β model, and we obtained \( M_{\text{E}} \) new = \( 1.1_{-0.2}^{+0.3} \times 10^{13} M_\odot \), which can explain 21–76\% of \( M_{\text{E}} \). Note that, the center position of the main cluster has a significant offset from the Eye of Horus, and the galaxy distribution suggests that the Eye of Horus has complex mass structures along the line of sight. There might be substructures along the line of sight, which are not considered in this work.

This is the first X-ray follow-up observation of the strong lens system discovered by Subaru-HSC, and we are planning to observe other strong lens systems with XMM-Newton and Chandra. Detailed modeling of the lensing of the Eye of Horus will be done, taking into account the result of this paper. When these observation and modeling are completed, we will be able to obtain robust constraint of the cosmological parameters and the gravitational structure of the distant galaxy.

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