TRACING THE PECULIAR DARK MATTER STRUCTURE IN THE GALAXY CLUSTER Cl 0024+17 WITH INTRAcluster STARS AND GAS

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ABSTRACT

Intracluster light (ICL) is believed to originate from the stars stripped from cluster galaxies. They are no longer gravitationally bound to individual galaxies, but to the cluster, and their smooth distribution potentially makes them serve as much denser tracers of the cluster dark matter than the sparsely distributed cluster galaxies. We present our study of the ICL in the galaxy cluster Cl 0024+17 using both Advanced Camera for Surveys (ACS) and Subaru data, where we previously reported the discovery of a ring-like dark matter structure with gravitational lensing. The ACS images provide much lower sky levels than ground-based data, and enable us to measure relative variation of surface brightness reliably. This analysis is repeated with the Subaru images to examine if consistent features are recovered despite a different reduction scheme and different instrumental characteristics. We find that the ICL profile clearly resembles the peculiar mass profile, which stops decreasing at $r \sim 50''$ ($\sim 265$ kpc) and slowly increases until it turns over at $r \sim 75''$ ($\sim 397$ kpc). This feature is seen in both ACS and Subaru images for nearly all available passband images while the features are in general stronger in red filters. The consistency across different filters and instruments strongly rules out the possibility that the feature might come from any residual, uncorrected calibration errors. In addition, our re-analysis of the cluster X-ray data shows that the peculiar mass structure is also indicated by a non-negligible $3.7\sigma$ in Chandra and $2.4\sigma$ in XMM-Newton bump in the intracluster gas profile when the geometric center of the dark matter ring, not the peak of the X-ray emission, is chosen as the center of the radial bin. The location of the gas ring is closer to the center by $\sim 15''$ ($\sim 80$ kpc), raising an interesting possibility that the ring-like structure is expanding and the gas ring is lagging behind perhaps because of the ram pressure if both features in mass and gas share the same dynamical origin.

Key words: cosmology: observations – dark matter – galaxies: clusters: individual (Cl 0024+17) – galaxies: high-redshift – gravitational lensing: weak – X-rays: galaxies: clusters

Online-only material: color figures

1. INTRODUCTION

Intracluster light (ICL), which was discovered by Zwicky (1951), is believed to originate from the stars stripped from cluster galaxies. Although details are still in dispute, a number of studies suggest that both the scatter of stars during the brightest cluster galaxy formation (e.g., Gerhard et al. 2007) and the tidal disruption of dwarf galaxies (e.g., Milos et al. 2005) are among the dominant mechanisms of the ICL production. These stars are in general considered bound not to any individual galaxy, but to the cluster mass. If a large fraction of the ICL is produced during the assembly of the brightest cluster galaxies (e.g., Murante et al. 2007), the dynamically collisionless property of the intracluster stars potentially allows us to use ICL as visible tracers of underlying dark matter at least in the central region of the cluster.

Observationally, however, the quantitative study of ICL is difficult. The typical surface brightness of ICL is often quoted as $\sim 1\%$ or less of the night sky from the ground. At this faint level, instrumental systematic effects such as residual flat fielding, scattered lights of bright stars, etc., become critical issues. In addition, most galaxy edges continuously blend into ICL, which obviously causes an ambiguity in determining where the galaxy light stops and ICL begins.

In this paper, we present a study of ICL in the galaxy cluster Cl 0024+17 at $z = 0.4$, where we recently discovered a peculiar ring-like dark matter structure (Jee et al. 2007, hereafter J07). The two-dimensional mass reconstruction of J07 shows that the core of the cluster is surrounded by an $r \sim 0.4$ Mpc ring-like overdense region. The feature is strongly constrained by coherent fluctuation of background galaxy shapes across the $r \sim 0.4$ Mpc circle (weak lensing) signaling the sudden change of the density slope. Of course, it is tempting to try to detect the peculiar dark matter structure with the cluster galaxies (e.g., Qin et al. 2008). However, because the density contrast of the feature with respect to the neighboring region is low ($\sim 5\%$), the sparsely distributed galaxies cannot provide sufficient statistics to overcome the shot noise even if the cluster galaxy membership identification is next to perfect. This is the reason that here we investigate, instead, the intracluster stars, which diffusey distribute in the cluster potential and thus sample the underlying dark matter much more densely. In this investigation, the measurement accuracy is not limited by the Poissonian scatter as in the study using galaxies, but by the ability to control various systematics critical to precision surface photometry.

We employ two sets of data: Hubble Space Telescope Advanced Camera for Surveys (HST/ACS) and Subaru/Suprime-Cam images. Space-based imaging provides significant advantage over ground-based effort mainly because the sky is substantially darker (e.g., $\sim 1$ and $\sim 3$ mag fainter in the $r$ and $z$ bands, respectively). Also, as the instrument is above the atmosphere, there is no cumbersome, time-dependent airglow effect, which often prevents stable calibration. However, unfortunately, there have been no ICL studies so far with the HST/ACS data. This is because the pipeline flat-fielding accuracy $\sim 1\%$ (Mack et al. 2002) has been considered insufficient to enable such studies. Therefore, we undertake this time-consuming task of producing/verifying HST/Wide Field Channel (WFC) flats of the images.
using “blank images” before we proceed with the ICL measurements. One drawback in using ACS data is the small field of view of the instrument, which only covers a $3^\prime \times 3^\prime$ region. Because the existing ACS data of the cluster were taken without any plan for this kind of study, the instrument pointing was almost fixed to the center of the cluster (with only a few tens of pixels dither to fill the two CCD gap), and thus care must be taken to minimize the ICL contamination in determining the background level.

Although the sky is much brighter, the Subaru/Suprime-Cam images provide a few critical crosschecks. First, the large field of view of the Suprime-Cam allows us to estimate the background level directly, which is important in determining the net amount of ICL and assessing the degree of the aforementioned ICL contamination in the HST/ACS measurements. Second, the Subaru data include the NB$_{912}$ narrow band image, which Kodama et al. (2004) used to probe H$\alpha$ emission as a measure of ongoing star formation of the cluster at $z = 0.4$. The sky level in this narrow band is about 1.5 mag darker than in the broadband $z'$ filter, while the narrow passband gives high contrast to the H$\alpha$ emission at $z = 0.4$ relative to continuum sources at different redshifts. Third, various instrumental signatures including the point-spread function (PSF), internal reflection, obscuration, geometric distortion, etc., are different from ACS. Hence, if a significant feature clearly revealed in one instrument is absent in the other, this indicates that the feature might come from some residual calibration errors or time-dependent sources. In contrast, detection of a consistent feature in both images provides evidence against these systematics.

The hot intracluster gas also samples the underlying dark matter very densely, although its collisional nature biases the distribution from that of dark matter. A common isothermal $\beta$ model assumes $\rho_{gas} \propto \rho_{DM}^\beta$ and $\epsilon_{ff} \propto n_e^2$, where $\epsilon_{ff}$ and $n_e$ are the free–free radiation emissivity and the electron density, respectively. Therefore, X-ray profiles in general are more centrally peaked than mass profiles. Also, as observed in many respects. Therefore, X-ray profiles in general are more centrally peaked than mass profiles. Also, as observed in many

Table 1

| Filter    | Visits | Total Exp. Time (s) | Mean Sky Level (mag arcsec$^{-2}$) | Sky Level Variation Between Visits (%) |
|-----------|--------|---------------------|------------------------------------|----------------------------------------|
| F435W     | 5      | 6435                | 23.1                               | 11                                     |
| F475W     | 4      | 5072                | 22.9                               | 4                                      |
| F555W     | 4      | 5072                | 22.6                               | 3                                      |
| F625W     | 7      | 8971                | 22.2                               | 8                                      |
| F775W     | 8      | 10144               | 22.2                               | 2                                      |
| F850LP    | 6      | 16328               | 22.1                               | 2                                      |

In this paper, we adopt a $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.3$, and $h = 0.7$ cosmology, where the plate scale is 5.3 kpc arcsec$^{-1}$ at the redshift of the cluster $z = 0.4$. The quoted uncertainties are at the 1$\sigma$ ($\sim 68\%$) level.

2. OBSERVATIONS AND REDUCTIONS

2.1. ACS Data Reduction

The cluster was observed with the WFC of the ACS in 2004 November. A single pointing ($\sim 3.3^\prime \times 3.3^\prime$ field of view) is centered near the cluster core ($\alpha_{2000} = 00^h 26^m 35^s, \delta_{2000} = 17^\circ 09^\prime 43^\arcsec$) with integrations of 6435 s, 5072 s, 5072 s, 8971 s, 10,144 s, and 16,328 s in the F435W, F475W, F555W, F625W, F775W, and F850LP filters, respectively. The low-level CCD processing was carried out using the STScI standard ACS calibration pipeline (CALACS; Hack et al. 2003) with some important modifications as follows. CALACS applies the LP-flats derived from both the laboratory before launch (Bohlin et al. 2001) and the 47 Tuc stars on orbit (Mack et al. 2002). We find that these pipeline flats deviate from sky flats at the $\lesssim 0.5\%$ level (see Section 2.3.1 for details). This level of inaccuracy should be corrected prior to ICL measurement although the sky level of HST images is 1–3 mag fainter. We applied these residual sky flats to these CALACS-processed FLT images. Careful inspection of these results reveals that the amplifier-dependent (quadrant-to-quadrant variation) bias at the level of $\sim 1$ DN were present in some frames. We fix these quadrant-to-quadrant variations by comparing the medians of the two adjacent strips ($\sim 100$ pixel width) evaluated after masking out astronomical objects and cosmic rays. In principle, these additive biases are supposed to be corrected before the application of the flats, which are multiplicative. However, as the bias is small and the flats are already close to unity, the errors arising from reversing the order of these two operations are negligible.

We measured sky levels in each frame through iterative sigma-clipping and subtracted the values before stacking. Table 1 summarizes mean sky levels for each filter. The final high-level processing involving geometric distortion correction and cosmic-ray removal was performed using the “apiss” pipeline (Blakeslee et al. 2003). We used nearest neighbor interpolation in drilling (Fruchter & Hook 2002). This is different from the procedure of J07, where the Lanczos3 (windowed sinc function) kernel is employed. The Lanczos3 kernel provides a sharp PSF, and thus suitable for weak-lensing studies. However, this kernel correlates neighboring pixels and artificially reduces noise fluctuation ($\sim 8\%$) although the degree of the correlation is found to be much lower than other commonly selected kernels.
such as square, Gaussian, etc. (Mei et al. 2005). Our choice of the nearest neighbor interpolation is to prevent any potential distortion of the intrinsic noise power spectrum due to drizzling.

2.2. Subaru Data Reduction

We retrieved the archival Subaru images of the cluster from SMOKA.1 The data were taken in 2002 September 7 with the prime-focus camera (Suprime-Cam; Miyazaki et al. 2002) in the NB$_{912}$ ($\lambda_{\text{eff}} = 9139$ Å, FWHM = 134 Å), $B$, $R_c$, and $z'$ filters with integrations of 10,800 s, 3600 s, 5280 s, and 1980 s, respectively. The number of visits per filter and the sky level variation are summarized in Table 2. The Suprime-Cam focal plane is tiled with $2 \times 5$ CCDs covering an area of $30' \times 27'$. Because we are only interested in the central region of the cluster, we only used the central six CCDs, which still cover a significantly large area ($20' \times 27'$).

The Suprime-Cam data reduction software SDFRED (Yagi et al. 2002; Ouchi et al. 2004) was used to subtract overscan, mask out regions affected by Acquisition and Guide (AG) probe and bad pixels, perform flat fielding (see Section 2.3.2 for details of our sky flat creation), and correct geometric distortion. The sky subtraction procedure of SDFRED removes small-scale sky variations, which undesirably distorts the ICL structure and the large-scale PSF profiles. Thus, we replace this step with our manual procedure summarized as follows. Each flat-fielded, $20' \times 27'$ frame shows $\lesssim 1\%$ sky gradient. This type of residual gradient is common and is attributed to night-by-night atmospheric effects rather than instrumental flat changes. In general, the pattern is monotonic and can be removed by modeling the gradient with a low-order polynomial plane. In this procedure, care must be taken to mask out extended PSF wings of bright stars, galactic cirrus, and the central region of the cluster ($3' \times 3'$), as well as resolved astronomical objects. Masking out PSF wings of bright stars was not difficult for several $m_r = 10$–12 mag stars inside the image. However, there is one $m_r \lesssim 7.5$ mag star outside ($\sim 1'$ away) the camera’s field of view, which causes severe scattered light in the southwestern corner. Because of the large scale ($\sim 4'$) of the feature, it is difficult to disentangle this scattered diffuse light from the sky gradient. Therefore, we chose to model/subtract this scattered light and the residual sky gradient at the same time by fitting a fourth-order polynomial plane to the entire field. It is possible that any imperfection in this procedure increases a large-scale sky level fluctuation beyond the flat-fielding accuracy. Therefore, we examined sky levels at random locations, and verified that the variation is consistent with what we expect from the flat-fielding errors.

After we subtracted the mode from each frame, we determined the spatial alignment and flux scaling between frames using bright non-saturated stars. This information was provided to SDFRED to create the final mosaic images. Zeropoints were evaluated by comparing photometry with that measured from the ACS images. We verified that these zeropoints are consistent with the values independently determined by Kodama et al. (2004), who kindly provided us with their results.2

We display in the top panel of Figure 1 the color-composite ACS and Subaru color images of Cl 0024+17 and two-dimensional ICL map. The top panel shows the central $10' \times 10'$ region of the color-composite Subaru image. White circles denote spectroscopic cluster members ($0.37 < z < 0.42$). The yellow outline illustrates the $3' \times 3'$ region observed with ACS. The ACS color-composite image is shown separately in the lower left panel. The two red dashed circles delineate the $r \sim 40''$ and $r \sim 70''$ radii, across which a sudden change of slope in the ICL profile occurs. The lower right panel displays the diffuse light in ACS F625W image. This two-dimensional ICL image is created by masking out astronomical objects, subtracting bright stars, and then applying $3' \times 3'$ box median smoothing. The color scale is linear. The diffuse light extends toward the northwestern substructure indicated by the cluster members and the mass reconstruction of Kneib et al. (2003).

(A color version of this figure is available in the online journal.)

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1 http://smoka.nao.ac.jp/

2 Kodama et al. (2004) used Vega-based magnitude system, while in the current paper all the magnitudes are given in the AB system.

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Table 2

| Filter | Visits | Total Exp. Time (s) | Mean Sky Level at Zenith (mag arcsec$^{-2}$) | Sky Level Variation Between Visits (%) |
|--------|--------|---------------------|------------------------------------------|----------------------------------------|
| $B$    | 3      | 3600                | 22.6                                     | 2                                      |
| $R_c$  | 11     | 5280                | 21.2                                     | 3                                      |
| $z'$   | 8      | 1980                | 19.2                                     | 5                                      |
| NB$_{912}$ | 6   | 10800               | 20.7                                     | 11                                     |

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Figure 1. ACS and Subaru color images of Cl 0024+17 and two-dimensional ICL map. The top panel shows the central $10' \times 10'$ region of the color-composite Subaru image. White circles denote spectroscopic cluster members ($0.37 < z < 0.42$). The yellow outline illustrates the $3' \times 3'$ region observed with ACS. The ACS color-composite image is shown separately in the lower left panel. The two red dashed circles delineate the $r \sim 40''$ and $r \sim 70''$ radii, across which a sudden change of slope in the ICL profile occurs. The lower right panel displays the diffuse light in ACS F625W image. This two-dimensional ICL image is created by masking out astronomical objects, subtracting bright stars, and then applying $3' \times 3'$ box median smoothing. The color scale is linear. The diffuse light extends toward the northwestern substructure indicated by the cluster members and the mass reconstruction of Kneib et al. (2003).

(A color version of this figure is available in the online journal.)
Figure 2. Residual sky flats in the six ACS/WFC broadband filters. These flats are created from the pipeline-reduced FLT files, and should reveal any residual features that are not corrected by the pipeline LP-flats (see the text for details in the procedure). The displayed gray scale is linear. The rms residual is \( \sim 0.5\% \). The most outstanding large-scale feature is the donut-like pattern particularly clear in F775W and F850LP. This residual feature may arise from the limited accuracy of the polynomial interpolation in the L-flat creation or from the pattern of the deviation and thus the impact of the reported inaccuracy on our ICL measurement. Therefore, we decided to independently create sky flats for all six ACS filters used for the Cl 0024+17 observations.

We collected 90–300 blank sky images for each filter from the STScI archive. We avoided images, which have large extended sources (e.g., nearby galaxies), many bright stars (e.g., globular clusters), or diffuse light (e.g., ICL in galaxy clusters, galactic cirrus, etc.). The selected images were manually examined, and discarded if any noticeable sky gradient is present. It is well known that quadrant-to-quadrant variation (1%–3% of background counts) is present in WFC images (see Sirianni et al. 2005 for description of the problem). Unless corrected for, these features are clearly visible in the final sky flat because the pattern is not completely random. We fix these quadrant-to-quadrant variation by comparing the medians of the two adjacent strips (\( \sim 100 \) pixel width) after masking out astronomical objects and cosmic rays. Then, we median-smooth each image with a box size of 32 pixels, and normalize the image by dividing it by the mode of the image. The final, median-stacked image of these normalized, median-smoothed images shows the residual flat-fielding error because we perform the task on FLT files that have already been applied the pipeline LP-flats. We show in Figure 2 these residual sky flats. Table 3 lists the number of images that we used for the creation of sky flats for each filter, the deviation from the pipeline flat, and the accuracy of the residual sky flat that we estimate by bootstrapping. The \( \leq 0.1\% \) accuracy in flat fielding implies that we can probe the surface brightness limit down to the \( \mu \sim 30 \) mag arcsec\(^{-2} \) level in nearly all ACS filters if flat fielding is the only dominant source of errors.

Our sky flats confirm the claim of Mack et al. (2005) and Pavlovsky et al. (2006) on the \( \leq 0.2\% \) accuracy of the pipeline LP-flats. The most notable large-scale structure is the donut-like pattern particularly clear in red filters (the difference in residual between the center of the donut pattern and the trough (\( \sim 1’ \) away) is \( \sim 0.5\% \) and \( \sim 2\% \) in F775W and F850LP, respectively). This residual feature is also mentioned by Pavlovsky et al. (2006), and they suggest that this might be due to the difference in spectrum between 47 Tuc stars and the sky. While we agree that the difference in color might be a plausible source of the residual, we expect the residual to be still observable even if there is no color difference between 47 Tuc stars and the sky.

The \( \sim 2\% \) flat-fielding error (i.e., the reported difference between the LP-flats and the STScI sky flats), if present on a large scale, is of concern for the investigation of the ICL features that this paper studies; for example, this will limit our ability to perform surface photometry to the \( \mu \leq 27 \) mag arcsec\(^{-2} \) regime in the F625W filter. Because the sky flats of the STScI are not yet publicly available, it is impossible to determine the pattern of the deviation and thus the impact of the reported inaccuracy on our ICL measurement. Therefore, we decided to independently create sky flats for all six ACS filters used for the Cl 0024+17 observations.

The ACS flats used by the current pipeline of the STScI, called LP-flats, were derived by combining the factory-measured P-flats before launch (Bohlin et al. 2001) and the inflight L-flats (Mack et al. 2002), which correct the pixel-to-pixel and the low-frequency variations, respectively. The L-flats were created directly for the filters F435W, F555W, F606W, F775W, F814W, and F850LP by observing stars in 47 Tuc, and indirectly for the remaining filters by interpolating the direct measurement results. Mack et al. (2005) report that the LP-flats are expected to reduce field-dependent sensitivity variation down to \( \leq 1\% \) for the first six filters, and \( \leq 2\%–3\% \) for the interpolated filters. Pavlovsky et al. (2006) mention that their investigation of the sky flats constructed from GOODS images for the F606W, F775W, and F850LP filters are in good (<2\%) agreement with the pipeline LP-flats.

### Table 3

| Filter   | Number of Used Images | Deviation from Pipeline Flats | Accuracy (\%) |
|----------|-----------------------|------------------------------|---------------|
| F435W    | 90                    | 0.5                          | 0.08          |
| F475W    | 138                   | 0.4                          | 0.07          |
| F555W    | 92                    | 0.4                          | 0.06          |
| F625W    | 155                   | 0.5                          | 0.07          |
| F775W    | 154                   | 0.4                          | 0.07          |
| F850LP   | 312                   | 0.7                          | 0.08          |

5 The FITS images of these ACS residual flats are publicly available upon request.

The ACS flats are created from the pipeline-reduced FLT files, and should reveal any residual features that are not corrected by the pipeline LP-flats (see the text for details in the procedure). The displayed gray scale is linear. The rms residual is \( \sim 0.5\% \). The most outstanding large-scale feature is the donut-like pattern particularly clear in F775W and F850LP. This residual feature may arise from the limited accuracy of the polynomial interpolation in the L-flat creation or from the pattern of the deviation and thus the impact of the reported inaccuracy on our ICL measurement. Therefore, we decided to independently create sky flats for all six ACS filters used for the Cl 0024+17 observations.

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The sky flats measure both sensitivity and projected pixel area (i.e., due to geometric distortion) effects, whereas the latter is difficult to measure without bias using stellar photometry alone unless the PSF is sufficiently oversampled.\(^4\)

On the center of the donut-like feature in F435W and F475W, there is a strong indication that the pipeline flats overcorrect the sensitivity in this region. Comparing these residual sky flats with the pipeline flats also reveals that there are a few dust-moats (e.g., bottom of F555W and center of F625W) that were not included in the pipeline LP-flats. Finally, it is clear that a grid-like pattern exists in all six filters shown here. The feature is most (least) obvious in the F850LP (F625W) filter. The average distance between grids is ∼60 pixels. Because this checkerboard pattern does not change in size and location as we vary smoothing kernels and sizes, we conclude that the pattern is not an artifact of our 32 pixel median smoothing. The exact cause of the checkerboard pattern has not yet been determined. Nevertheless, we suspect that this particular residual pattern might be the remnant of the ACS CCD fabrication process that is not corrected by the P-flat. The peak-to-valley variation of the feature amounts to ∼1% in F850LP.

### 2.3.2. Subaru Flat Fielding

We retrieved blank images taken during the 2002 August–September period from the Subaru archive. As in the case for ACS, we manually examined and discarded frames that are not adequate for flat-field generation (e.g., the presence of diffuse emission, extremely saturated stars, crowded stellar fields, etc.). Bad pixels and the vignetted areas by the AG Probe on the top five CCDs were masked out in the remaining frames. Astronomical objects were identified and masked out by searching for five or greater continuous pixels above 1.5 times the sky rms. After median-smoothing each frame with a box size of 16 × 16 pixels, we normalized the image using its mode, and then median-stacked all frames to create preliminary sky flats. These preliminary sky flats allow us to refine the evaluation of the previous modes and the detection of astronomical objects to be masked out. Therefore, we obtained the final sky flats by iteratively evaluating the modes, detecting objects, and creating flats as done by Morrison et al. (1997). One important modification to the Morrison et al. (1997) method is that we removed low-frequency residual sky gradients (<1%) by fitting second-order polynomial planes. As noted by many authors (e.g., Feldmeier et al. 2002), each frame possesses non-negligible sky gradient due to many atmospheric effects even if a perfect sky flat is applied. This removal of the residual sky gradient further reduces the width of the sky distribution within a frame, which also helps us to mask out faint astronomical objects more efficiently. After a few iterations, we obtained converged master sky flats.

The accuracy of these final sky flats was not limited by photon statistics thanks to the large light-collecting power of the Subaru telescope, but by the aforementioned large-scale sky variations in input frames. Therefore, we estimated the accuracy of the sky flat by bootstrap-resampling the input frames. The estimated error for the six central CCDs that we keep for the cluster reduction is on average ∼0.07% (see Table 4 for the individual filters). The 0.07% accuracy in flat fielding, if this is the sole source of systematics, allows us to probe the surface brightness ∼8 mag deeper than the sky level. For the B filter, this surface brightness limit is ∼30.5 mag arcsec\(^{-2}\), similar to the value in ACS data whereas for the z′ filter, this limit implies that we can reach down to the μ ∼ 27.5 mag arcsec\(^{-2}\) level because of the high sky level (μ ∼ 19.2 mag arcsec\(^{-2}\)). However, it is important to remember that the quoted accuracy represents the large-scale error within the entire field (20′ × 27′). While this large-scale error is a major source of uncertainty in our determination of the background level (thus limiting the accuracy in absolute ICL level measurement), the flat-fielding error affecting the relative significance of the ICL profile is the uncertainty of the flats within the central 3′ × 3′ region. As this area occupies only ∼1.7% of the total 20′ × 27′ area, the flat accuracy within the region is significantly (a factor of 2) better than the accuracy across the field. In addition, the dithering of the observation improves the flatness further, turning systematics into statistics. Because the current paper is focused on the structure of the ICL profile within this region, we distinguish these residual errors from the absolute errors when necessary.

For a sanity check, we compare these sky flats with dome flats. For the B, z′, and NB\(_{912}\) filters, high signal-to-noise ratio (S/N) dome flats were taken along with the cluster Cl 0024+17 on the same night (2002 September 7). For the R\(_c\) filter, the closest dome flats in time were taken on 2002 September 4. Again, we limited our analysis to the central six CCDs. We found an rms difference of ∼0.2% on average, which suggests that the Suprime-Cam flats are time-stable at least over this two-month period. Furthermore, we note that this ∼0.2% discrepancy is dominated by a large-scale gradient, and we suspect that this is caused by the non-uniformity of the dome screen. When this gradient is removed by second-order polynomial modeling, the agreement becomes ∼0.1%.

### 2.4. Object Detection and Masking

As it is impossible to model the surface brightness profile of individual galaxies accurately and to subtract the contribution without introducing biases in our ICL study, we choose to mask out galaxies. In order to obtain consistent masking regions across filters, we used a single detection image for each instrument. For the ACS data set, this image is automatically generated by apsis from weight-averaging all six filter images. For the Subaru data, the R\(_c\)-band image is significantly deeper than the rest, and thus this R\(_c\) image is chosen to detect astronomical objects. We detect objects via SExtractor by searching for at least five connected pixels above 1.5 times sky fluctuation.

Because galaxy light continuously blends into background light, it is important to define the size of the masking area very carefully. An ideal masking size is to minimize the impact of the diffuse wing of objects while still leaving a sufficient number of background pixels usable for the ICL measurement. Obviously, an ellipse defined by SExtractor’s semimajor and semiminor axes does not sufficiently mask out diffuse wings of galaxy light. Hence, we enlarged the masking size by integer multiples of these axes (we refer to these as “1x,” “2x,” “3x”,

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\(^4\) Imagine an extreme case where the PSF is severely undersampled and the stellar profile is confined to a single pixel. Then, the total flux in each CCD pixel only informs us of the sensitivity, not the projected pixel size.
Figure 3. Experiment with different masking sizes. We investigated the effect of the masking size on the centroids of the Gaussian curves by varying masking sizes and repeating the measurements. As an example, shown here is the result from the $r \sim 80''$ bin in F775W. The different Gaussian curves represent the results from different masking schemes. The vertical dashed lines show the corresponding centroids. We observe that the centroid converges when the majority and minor axes of the masking ellipse are three times or greater than SExtractor measurements. We conservatively selected five times the values given by SExtractor in defining our masking ellipses throughout the analysis. (A color version of this figure is available in the online journal.)

Figure 4. Extended PSF wings of ACS/WFC (left) and Subaru/Suprime-Cam (right). The normalization is chosen in an arbitrary way so that the profiles from different filters approximately overlap at $r < 20''$. The ACS results are obtained from the archival observation of the star HD39060 (Beta Pictoris). The Subaru PSFs were measured from the brightest star ($r \sim 8.6$ mag) in the Cl 0024+17 image ($\sim 7''$) away from the cluster center. (A color version of this figure is available in the online journal.)
The residual error after PSF subtraction is estimated to be $\mu_R \gtrsim 31$ mag arcsec$^{-2}$, and thus should not affect our ICL measurement.

The lower right panel of Figure 1 displays the diffuse light of the cluster in the ACS F625W image. The galaxies and the stars are masked out/subtracted as described above. The image shown here is obtained after median-smoothed with a box size of $\sim 3'' \times 3''$. The color bar represents the intensity on a linear scale. The ICL distribution of CL0024+17 is somewhat asymmetric and extends northwest toward the secondary galaxy number density peak, which lies just outside the ACS field.

For Subaru images, our PSF model extends to $r \sim 5'$, and we subtracted all $m_R \lesssim 17$ mag stars while masking out the central region with magnitude-dependent radius. In the region overlapping the ACS field, care was taken in choosing masking radius so that the estimated residual surface brightness error outside the masking aperture is below the $\sim 30$ mag arcsec$^{-2}$ level.

### 2.5. Background Level Determination

The accuracy in the estimation of background sky level affects the fidelity of the ICL profile at large radii, and is one of the most significant sources of systematic errors in the current analysis.

For Subaru data, after we removed residual sky gradients and bright stellar profiles (Sections 2.2 and 2.4), we determined the background level from the $4' < r < 10'$ annulus. The inner radius of the annulus was determined by creating the radial profile of the surface brightness and then locating the region where the profile starts to flatten. The uncertainty of these background measurements should be dominated by large-scale flat-fielding errors and residual sky gradients because the statistical noise is only at the $\sim 10^{-3}$% level of the sky. We estimated the errors in the background level measurement by subsampling the sky within the $4' < r < 10'$ annulus. Table 5 displays these values in terms of fraction of the sky and the corresponding surface brightness level.

The small field of view of the ACS image does not allow us to obtain the background level far from the cluster center. If the ICL level within the ACS field is still non-negligible, the background level directly measured within the ACS images biases the ICL level artificially low. We considered performing photometric transformation from Subaru to ACS and estimating the corresponding surface brightness level of the ICL (thus indirectly determines the background levels) in ACS. However, it is difficult to prove that the two instruments in very different environments allow us to match the background level in this way. Therefore, we chose to estimate the background level still within the ACS field while minimizing the ICL contamination in the following way.

Inspection of the two-dimensional images of the Cl 0024+17 diffuse light reveals that the two-dimensional ICL distribution is highly asymmetric around the center. In the case of F625W (e.g., lower right panel of Figure 1) the surface brightness in the northwestern corner is $\mu \sim 27$ mag arcsec$^{-2}$, whereas it is $\mu \gtrsim 31$ mag arcsec$^{-2}$ in both the southeastern and the southwestern corners. Because this high S/N pattern is also supported by other images of both ACS and Subaru, the two-dimensional feature is believed to represent the intrinsic distribution of the ICL. In addition, the spatial distribution of the cluster galaxies is similar to this two-dimensional ICL map (top panel of Figure 1). Therefore, we argue that if we measure the background level at $r > 80''$ from the ACS image while excluding the northwest region, we can minimize the influence of the ICL. This argument is further supported by our experiment with the Subaru image, which shows that the background level measured in this way (i.e., cropping the $3' \times 3'$ region to simulate the ACS field) is in good agreement with the result measured from the $4' < r < 10'$ annulus within the $\mu \simeq 30$ mag arcsec$^{-2}$ level.

### 2.6. X-ray Data Reduction

For the Chandra X-ray analysis, we followed the procedures described in J07, using the Chandra Interactive Analysis of Observations (CIAO) software version 3.3 and the Calibration Database (CALDB) version 3.2. The XMM-Newton data (taken on 2001 January for a total integration of 52.1 ks, 52.1 ks, and 48.3 ks for MOS1, MOS2, and PN, respectively) were retrieved from the XMM-Newton Science Operations Centre$^5$ and processed with the Science Analysis Software (SAS) version 7.1.2. We combined the three instrument data and applied the exposure map to obtain an exposure-corrected image. We detected point sources in the Chandra and used the results to mask both the Chandra and XMM-Newton exposure-corrected images before we measured the final X-ray surface brightness profile.

### 3. ICL ANALYSIS

#### 3.1. Measurement of the Radial Profile

We adopt the statistical approach of Uson et al. (1991) in measuring the radial ICL profile of the cluster. In their analysis of Abell 2029, they constructed histograms from the pixels in radial bins and demonstrated that for each bin the position of the Gaussian peak in the pixel intensity histogram is a fair indicator of the ICL levels. The skewness of the Gaussian, mainly caused by diffuse light from wings of astronomical objects, is a potential source of bias in this measurement. Uson et al. (1991) report that the bias introduced by this contamination is about 0.2% of the sky level at one core radius of the cluster if objects are left unmasked. As discussed in Section 2.4, our “$5' \times 5'$” masking scheme reduces the effect below the 0.02% level of the sky.

To illustrate our measurement scheme, we show in Figure 5 the histograms that we obtain in F775W after masking objects and subtracting stars. We set up radial bins out to $r \sim 100''$ ($\sim 530$ kpc) at an interval of $\Delta r = 8''$. The bottom curve represents the data in the $r = 8''$ bin. We displace the subsequent histograms vertically to improve readability. The top curve corresponds to the data in the $r = 104''$ bin. The filled squares and thick solid line trace the location of the Gaussian peaks. The uncertainties in determining the centroid of the Gaussian curve after including photon noise and flat-fielding errors are $\sim 0.5$ counts or $\mu \simeq 30$ mag arcsec$^{-2}$, smaller than the size of the filled square symbol. We choose the geometric center of the

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$^5$ The data are available at [http://xmm.esac.esa.int](http://xmm.esac.esa.int).
dark matter ring as the origin of the radial bin. The geometric center of the dark matter ring is $\sim 10''$ offset toward south from the peak of the X-ray emission (also the location of one of the brightest cluster galaxies).

Figure 6 shows 10 ICL profiles that we measure from both ACS and Subaru data for all available passband data. The thick solid lines represent the surface brightness, while the dashed (dotted) lines show the $1\sigma$ limits without (with) including background level measurement errors. In the case of ACS, we arbitrarily assume that the error in background level measurement is at the 0.1% of the sky level (the statistical error is negligible). The Subaru profiles have much larger errors mainly because the sky levels are higher. Especially, in the $z'$ image the sky level is nearly 3 mag brighter than in the ACS F850LP image, and thus the 0.05% flat-fielding error is translated into $\mu \sim 27.5$ mag arcsec$^{-2}$, whereas the 0.1% flat-fielding error in the ACS F850LP corresponds to $\mu \sim 30$ mag arcsec$^{-2}$.

Despite the filter-by-filter variation in significance, it is remarkable that all profiles in Figure 6 share some conspicuous common features. The surface brightness in every profile decreases rapidly from the cluster center to $r = 40''-50''$. Then, it maintains its level out to $r \sim 70''$, where it starts to decrease again for increasing radius. The changes of the slopes at the two locations are nearly discontinuous, somewhat more sudden than the corresponding changes in mass slopes of J07; the significance of the feature should be evaluated using the inner error lines (dashed), which exclude the background level measurement errors. This striking consistency across different filters and instruments is the evidence against the possibility that the features come from any residual systematic errors.

The comparison of the ACS and Subaru results at the large radii help us to assess the degree of the ICL contamination.
in the background level for ACS. Although the difference in throughput curve between the instruments complicates the detailed comparison, there is no apparent indication that any significant systematic underestimation of the ICL level (or overestimation of the background level) is introduced in the ACS results; the ICL levels in corresponding filters between the two instruments are consistent within the errors.

3.2. Comparison of ICL Profile to Mass Profile

The peculiar mass density profile of Cl 0024+17 in J07 is characterized by the steep decline out to \( r \sim 50' \) (~265 kpc), the slow rise from \( r \sim 50' \) (~265 kpc) to \( \sim 75' \) (~397 kpc), and the modest decrease at \( r \gtrsim 75' \). The turnaround at \( r \sim 75' \) (~397 kpc) appears as the dark matter ring in the two-dimensional mass reconstruction. The ICL profiles in Figure 6 clearly signal these features of the J07 mass profile. Although the significance varies across filters and instruments, it is evident that all profiles change their slopes conspicuously at both \( r \sim 50' \) and \( r \sim 72' \) in a similar way as in the mass profile. Considering the size of the uncertainty (we exclude the background level uncertainty here because it does not affect the significance of the relative variation), the change of the profile slopes is significant in every panel except for the ACS F435W data, for which the major source of uncertainty comes from a low ICL-to-sky ratio. Of course, the most remarkable aspect of the results is the observation that all profiles closely resemble one another, which strongly rules out the possibility that the source of these features originates from uncorrected instrumental systematics.

In Figure 7, we overplot these ICL profiles on top of the mass profile of J07 after rescaling of the flux via the following form: \( I'(r) = a \times I(r) + b \). If intracluster stars are truly Poissonian tracers of underlying dark matter, a strict comparison would require no intercept in the transformation. However, considering the uncertainty of the background level determination in ICL measurement, the uncertainty of the mass profile caused by mass-sheet degeneracy, and the physical mechanism that ICL might be more centrally concentrated, we allow the intercept to vary in the fitting procedure. Furthermore, we limit the fitting range to the \( 20' < r < 75' \) region because at \( r < 20' \) the ICL measurement is hampered by severe masking of bright cluster galaxies, and at \( r > 75' \) the ACS data become progressively incomplete toward large radii. Also, for some filters ICL profile measurements are sensitive to the background estimation in this regime. The black solid line is the mass profile of J07. The open circles denote the results from the different filters in ACS, whereas the open diamonds represent the case for the Subaru images. The thick purple line delineates the mean ICL profile.

This direct comparison more graphically supports the above claim that the ICL of Cl 0024+17 mimics the peculiar mass profile. The mean ICL profile shows a sudden change of slope at \( r \sim 50' \) and \( r \sim 72' \) as does the mass profile. In addition, the difference among the results from different filters is remarkably small. Because the agreement is excellent over a large range of radii, this consistency should not be attributed to the rescaling of the profile.

We note, however, that the agreement between the ICL and mass profiles degrades at \( r \gtrsim 72' \). Apparently, the ICL profile changes its slope more suddenly at \( r \sim 72' \) than the mass. The difference among the ICL profiles is also slightly larger in this regime. It is tempting to view this as an indication that the ICL distribution is more centrally peaked than the cluster mass distribution. However, one should use caution in interpreting the difference. The ACS data do not provide complete azimuthal statistics at \( r \sim 80' \). Also, the ICL level in this range is sensitive to the background level determination.

The dashed line is a Navarro–Frenk–White (NFW) fit to the mass profile using the value in the \( 20' < r < 50' \) range. Both the cluster mass and ICL profiles deviate from this analytic model frequently used to describe relaxed clusters.

3.3. Is the Peculiar ICL Structure Local?

The consistent detection of the peculiar ICL feature of Cl 0024+17 from both ACS and Subaru data provides evidence that the feature does not come from any residual calibration errors. And the similarity between the ICL and mass profiles further adds to the credibility of the detection. However, one can raise a concern that our masking might miss a few low surface brightness objects that fortuitously occur at a similar distance from the cluster center. While we consider that this is very unlikely given the significance and the scale of the features, it is still useful to devise a test demonstrating that the features indeed come from a two-dimensional, quasi-symmetric diffuse light distribution, not from any localized concentration.

The most straightforward proof would be the revelation of the discussed feature in the two-dimensional ICL map. However, given the low contrast of the structure, it is extremely difficult, if not impossible, to produce a convincing diffuse light map of the cluster. The pixel histograms in Figure 5 that we discussed in Section 3.1 help us to quantitatively understand why it is next to impossible to see the feature in a two-dimensional map. As discussed already, the location of the Gaussian curve centroid is the indicator of the ICL level. The measurement leads to an uncertainty small enough (~30 mag arcsec\(^{-2}\)) for us to
give high significance to the relative variation of the centroids as a function of radius. However, the width of the Gaussian curve itself (i.e., the intrinsic pixel intensity distribution) is much larger than the relative variation of the centroids (i.e., ∼70 counts versus ∼2 counts), which makes it futile to attempt to detect the feature in a two-dimensional map.

A visual inspection of the two-dimensional ICL map (the lower right panel of Figure 1), nevertheless, reveals that there is some localized diffuse light in the northwestern quadrant; it appears that the diffuse light in this region is associated with several galaxies approximately on the r ∼ 72′′ circle. Hence, it is important to examine how significantly the ICL profile that we presented in Section 3.1 is affected by this apparent substructure. To address this issue, we divided the cluster field into four azimuthal regions and measured an ICL profile in each quadrant. The result from the F775W image is presented in Figure 8. Although there exists a quadrant-to-quadrant variation, the features seen in Figure 6 are also observed in each quadrant. Most of all, the ICL level stops decreasing at r ≃ 40′′–50′′ and increases out to r ≃ 70′′ in each panel. The sudden change of slope at r ∼ 72′′ is the strongest in the northwest and southeast quadrants. The profile from the northeast quadrant shows a weak change of the slope at this location, whereas the slow rise of the profile between 40′′ ≲ r ≲ 70′′ is still clear. The southwest ICL profile possesses a sudden change of slope at r ∼ 50′′ and the surface brightness is increasing out to r ∼ 65′′. For this quadrant, the change of slope at r ∼ 72′′ is subtle, which suggests that the ring-like structure might not be strong there. Nonetheless, the interpretation is difficult because the surface brightness level at this location is very low (μ ≳ 29 mag arcsec −2) and thus the error is dominated by systematics.6

Therefore, from the above experiment we conclude that the ICL profile structures resembling the peculiar mass profile in J07 do not come from any localized substructure, but from a two-dimensional, quasi-symmetric distribution of diffuse light in Cl 0024+17.

3.4. ICL Color versus Galaxy Color

The color of ICL relative to the color of cluster galaxies potentially constrains the epoch at which most of the intracluster stars were stripped from the cluster galaxy. The literature roughly converges on the observation that ICL colors are approximately consistent with the galaxy colors, which suggests that intracluster stars may be just as old as cluster galaxies.

Considering the location of the 4000 Å break at z = 0.4 in the observed frame, we find that a F475W–F625W color gives good contrast between the cluster red sequence and the rest of the population in the field. The color–magnitude diagram in Figure 9(a) with this filter combination clearly shows the red sequence of the cluster in the ACS field (the red solid line approximately delineates the location). We display in Figure 9(b) the F475W–F625W color profile of the ICL. At large radii, the accuracy highly depends on how well we can determine the net amount of ICL. Therefore, the biases in the background level determination cannot be neglected here. We assumed that this bias is at the 0.1% of the sky level.

We find that the ICL color at small radii (r ≲ 40) is consistent with that of the cluster red sequence while the color profile tends to become bluer with increasing radius. This trend is in agreement with the general expectation that cluster galaxies are bluer at larger cluster-centric radii. Robust interpretation of Figure 9(b) would be possible if we use a population synthesis model assuming several different star formation histories. While we acknowledge the importance of this study in determining the age of the progenitor population of the ICL, this extensive analysis is beyond the scope of the current paper. However, one possible interpretation of Figure 9 is that for the Cl 0024+17 cluster the observed ICL might be the result of ongoing stripping of stars (e.g., Moore et al. 1996). If dominant fraction of the ICL stars were stripped a few Gyr earlier than the current epoch and have evolved passively since then, we would expect to observe that the intracluster stars are redder than the cluster galaxies because the cluster galaxies continue to form new stars (e.g., Sommer-Larsen et al. 2005).

3.5. ICL Fraction

Together with ICL color, the total amount of light in intracluster stars relative to the total cluster light is also an important quantity in helping us to infer the production history of intracluster stars. In order to identify the total cluster light, we combined the photometric redshift catalog of J07, and the publicly available spectroscopic catalog of Moran et al., (2005). Figures 3 and 4 of J07 demonstrate that the photometric redshifts estimated from six ACS filters with Hubble Deep Field North (HDFN) prior give highly consistent results with the spectroscopic measurements and reliably identify the cluster members.
Figure 9. Galaxy color vs. ICL color. (a) Color–magnitude diagram in the ACS field. We used SExtractor’s isophotal magnitude to compute the galaxy colors, while the F625W magnitude in the X-axis is SExtractor’s MAG_AUTO. The red solid line approximately indicates the location of the cluster red sequence. (b) ICL color profile as a function of radius. The dotted lines represent the 1σ uncertainty including errors in photon statistics, flat-fielding inaccuracy, and background level determination. We assume that the error in the background level determination is at the 0.1% level of the sky.

Table 6
ICL fraction in Cl 0024+17

| Filter  | r < 200 kpc (%) | r < 500 kpc (%) |
|---------|-----------------|-----------------|
| F475W   | 35 ± 6          | 38 ± 12         |
| F555W   | 35 ± 4          | 37 ± 9          |
| F625W   | 35 ± 2          | 35 ± 5          |
| F775W   | 27 ± 1          | 26 ± 3          |
| F850LP  | 29 ± 1          | 30 ± 3          |

We replaced the photometric redshifts if their spectroscopic redshifts are known (∼140 objects) and used this merged catalog to select the cluster members of Cl 0024+17. The rest of the procedure is identical to the one in our ICL measurement described in Section 3.1 except that (1) we did not mask out the cluster members and (2) took the mean value in each annulus instead of the location of the Gaussian peak.

Figure 10 shows the ICL fraction measured from the five ACS filter images; we omit the results for F435W, whose error bars are substantially larger than the rest. As in the case for the ICL color measurement, the ICL fraction at large radii is sensitive to the background level determination and we again assume 0.1% of the sky level for the uncertainty. It appears that the mean level of the ICL fraction somewhat depends on the used filter. Although this observed trend possesses low significance at large radii due to the systematics in the background level determination, the results at small radii (r ∼ 40″) show that the ICL fraction is on average higher in blue filters (i.e., F475W, F555W, and F625W).

In order to estimate the cumulative ICL fraction within an aperture, we need to assume the behavior of the ICL profile at r < 15″, where our masking procedure left no area for direct ICL measurement. Extrapolating the central value using the trend at r < 40″, we obtain the results in Table 6. The uncertainties are determined from Monte Carlo simulations while the correlations between points are taken into account. The literature does not converge on the ICL fraction, and perhaps this represents rather a wide range of values for different clusters than scatters in measurements. Certainly, the ICL fraction (≥30%) of Cl 0024+17 that we quote here indicates that the cluster might be near the high end of the distribution. Tyson et al. (1998) determined the ICL fraction for Cl 0024+17 to be 15% ± 3% within the r ∼ 100 kpc region. Because their analysis is based on the Wide Field Planetary Camera 2 (WFPC2) data, which covers only ∼50% of the ACS field, we suspect that their background level measured within the WFPC2 field might be highly biased due to the significant ICL level; the ICL profile in
our study shows that the surface brightness level remains high out to $r \sim 70''$.

Given the numerical studies suggesting that most of intracluster stars become unbound at $z < 1$ with no preferred epoch (e.g., Murante et al. 2007), the high ICL fraction of Cl 0024+17 at $z = 0.4$ is somewhat unexpected. However, if the high-speed encounter scenario of Czoske et al. (2002) for Cl 0024+17 is considered, it is plausible that the collision of two equal-mass subclusters 1–2 Gyr ago might have liberated unusual amount of stars in the cluster galaxies.

4. INTRACLUSTER MEDIUM PROFILE OF Cl 0024+17

Although the collisional and dissipative nature makes its spatial distribution often differ from that of dark matter, intracluster gas distribution in a galaxy cluster strongly signals the structure of the cluster potential dominantly determined by the cluster dark matter. Therefore, whether or not one can find a good spatial agreement between the two results, a detailed comparison often provides an insight into the dynamical history of the two cluster constituents (e.g., Jee et al. 2005; Clowe et al. 2006).

Our previous analysis of the Chandra data of Cl 0024+17 confirmed the unusual X-ray profile of the cluster originally reported by Ota et al. (2004). The central excess of the X-ray photons only allows us to describe the profile with a superposition of two isothermal profiles of different $\beta$ parameters. Nevertheless, the X-ray surface brightness profile of J07 did not show any features reminiscent of the reported dark matter profile.

However, repeating the J07 analysis with a different choice of the cluster center shows that there presents a 3.7$\sigma$ bump in the X-ray profile at $r \sim 60''$ as shown in Figure 11. The result in the left panel is obtained when the center of the dark matter ring is chosen as the origin of the radial bins, whereas the right panel shows the X-ray profile when the center is placed on the peak of the X-ray emission as in the J07 analysis. It is worth noting that the distance between these two locations is only $\sim 10''$. The fact that this small change greatly alters the significance of the feature indicates that the contrast is low and the bump is associated not with any unidentified point source, but with smooth, azimuthal distribution of excess X-ray photons.

The X-ray surface brightness stops decreasing at $r \sim 50''$ and increases slowly until it suddenly drops again at $r \sim 60''$. The overall behavior is reminiscent of the features seen in both the ICL and mass profiles of the cluster.

Similar to the case in our ICL measurement, this X-ray feature becomes more credible if a consistent structure is observed in data from a different instrument. We present the result from the XMM-Newton in Figure 12. The large PSF of the instrument certainly smooths the aforementioned feature in the X-ray profile. However, the profile still shows a 2.4$\sigma$ bump at the same location.

5. DISCUSSION

5.1. Discrepant Mass Profiles in the Literature

The galaxy cluster Cl 0024+17 has been known for its large (a factor of 2 or more) mass discrepancy between gravitational lensing and X-ray results. However, the large mass discrepancy from different lensing analyses has not received its due attention. We compare five different mass profiles found in the literature in Figure 13. Although some of the large discrepancy at small radii ($\lesssim 20''$) is due to the difference in the choice of the cluster center, it is remarkable that different profiles give a very wide range of mass density outside the location of the critical curve ($\sim 30''$).
demonstrate that the mass structure of the cluster Cl 0024+17 is
analysis combining the strong lensing constraints of Zitrin et al.
reveal the peculiar structure at
Discrepant mass profiles of Cl 0024+17 in the literature. The unit
Figure 13.
(r
the mass density increases from this point on until it drops at
transformation of the mass density:
refers to the invariant lensing observable under the following
degeneracy in gravitational lensing. Mass-sheet degeneracy
is not small, the transformation becomes more conspicuous
proper choice of
λ
mass profile would be transformed to match the Zitrin et al.
images have been identified. Hence, it may be possible that the
constraining the mass profile at
r
1), the transformation can be viewed as adding an
additional sheet of mass (hence, the term “mass-sheet”). When
κ
is not small, the transformation becomes more conspicuous
in change of slope. Indeed, most of the different mass profiles
in Figure 13 roughly overlap under this transformation with a
proper choice of λ and a centroid.

However, the J07 profile is unique in the sense that the density
does not decrease at \( r \gtrsim 50'' \). As repeatedly discussed above,
the mass density increases from this point on until it drops at
\( r \sim 75'' \). Therefore, it would be incorrect to claim that the
peculiarity of the J07 mass profile is attributed to unresolved
mass-sheet degeneracy because the invariant transformation
does not change the sign of the slope.

If the multiple image identification by Zitrin et al. (2009) is
flawless and the bias in their photometric redshift estimation is
negligible, their mass profile should be regarded as the most
accurately calibrated profile to date because the 33 multiply
imaged sources at different redshifts certainly provide strong
constraints on the mass slope. Nevertheless, it is important to
remember that these strong-lensing features are not useful in
constraining the mass profile at \( r \gtrsim 50'' \), where no multiple
images have been identified. Hence, it may be possible that the
J07 mass profile would be transformed to match the Zitrin et al.
(2009) profile at \( r \lesssim 50'' \). Nevertheless, the result should still
reveal the peculiar structure at \( r \gtrsim 50'' \) (with reduced density
because \( \lambda \) must be greater than unity in this case). A further
analysis combining the strong lensing constraints of Zitrin et al.
(2009) with the weak-lensing data is a subject of our future
investigation.

The diverse results in the literature shown in Figure 13 clearly
demonstrate that the mass structure of the cluster Cl 0024+17 is
still disputed in the community, and thus more concerted efforts
toward a better mass model, such as spectroscopic redshift
survey of the multiply lensed sources, high-resolution infrared
imaging aimed for better photometric redshift estimation of
background galaxies, etc., are desired. On the other hand, it
is important to investigate the issue with different observables.
Our study of the intracluster stars as potential tracers of the
underlying dark matter structure is one such approach, and here
we argue that the peculiar features of the ICL that we report in
this paper strongly favors the J07 result among the five models.
Of course, it is still an open question how well the intracluster
stars trace the underlying dark matter. While there is a consensus
that intracluster stars are not bound to individual galaxies but
to the cluster potential, the answer to this question certainly
depends on when, where, and how the ICL is produced. We
discuss the issue in Section 5.2.

5.2. Interpretation of the Similarity between ICL and Mass
Profiles

If intracluster stars are dominantly produced by truncation of
galaxy halos during the initial formation of a cluster (e.g., Merritt
1984), the dynamical history of the intracluster stars is as old as
the cluster itself. Hence, in this scenario we expect to observe the
strongest correlation between ICL and mass distributions. Many
N-body simulations, however, indicate that other mechanisms
such as high-speed encounters between cluster galaxies (Moore
et al. 1996), stripping from a cluster potential (Byrd & Valtonen
1990), stripping in galaxy groups falling into the cluster (Mihos
2005), etc., might also contribute significantly to the overall
production, which then would make it less straightforward to
interpret the ICL structure in conjunction with the mass
distribution. It is an open question which of these mechanisms
is most dominant.

Recently, Murante et al. (2007) investigated the origin of the
intracluster stars through a cosmological hydrodynamical
simulation. They reported that a dominant fraction (~50%) of
the intracluster stars are produced in the formation of the most
massive galaxy at the cluster center, which is consistent with the
observation that the ICL is more centrally concentrated than the
cluster galaxies (e.g., Zibetti et al. 2005). If cluster galaxies
are Poissonian, albeit sparse, tracers of underlying dark matter,
this suggests that perhaps the ICL profile might be more peaked
also than the cluster mass profile.

With this view in mind, the resemblance of the ICL profile
to the mass profile shown in Figure 7 may seem somewhat
surprising. However, it is important to remember that the ICL
profiles are rescaled to match the mass profile, and thus it is
trivially obvious that the agreement in the range \( 20'' \lesssim r \lesssim 50'' \)
indicates nothing more than that both the ICL and mass profiles
monotonously decrease in this regime. What deserves our
attention, nonetheless, is that both profiles change the slope
at \( r \sim 50'' \) by the same amount (of course, after rescaling is
applied), giving a good agreement out to \( r \sim 70'' \). The average
ICL levels between the \( r \sim 20'' \) and \( r \sim 50'' \) regions differ by
a factor of 5 while in mass the density ratio is less than a factor
of 2. Because the mean slope at \( 50'' \lesssim r \lesssim 70'' \) is much smaller
than the value at \( r \lesssim 50'' \), the ICL profile, although being much
steeper than the mass profile, could be brought to agree after
rescaling.

Therefore, our results presented here should not be interpreted
as a demonstration that the intracluster stars in Cl 0024+17 can
be used as direct (i.e., Poissonian) tracers of the underlying
dark matter. Our ICL profile measurement supports the view
that the dominant ICL production mechanism is associated with the formation of the brightest cluster galaxies at the cluster center, and thus their distribution is expected to be more centrally concentrated on average. However, dynamically old intracluster stars are given the chance to travel further away from the cluster center and mix with the cluster halo dark matter. Hence, the ICL profile should represent the dynamical history of the cluster in the central region, as well as the ICL production history.

The expectation that cluster outskirts might be severely depleted of intracluster stars may aid us in explaining the difference between the mass and ICL profiles at $r \gtrsim 72''$. As already discussed in Section 3.2, the ICL profiles change their slopes more suddenly at $r \sim 72''$ than the mass profile, and hereupon the ICL levels quickly approach the background level. It is plausible that this is because the initial ICL level is already low in this region before the dark matter structure is disrupted. Alternatively, we can consider the possibility that the J07 mass profile is biased at $r \gtrsim 75''$, and the real mass profile is similar to the level that is indicated by the ICL profiles. The radial mass profile in J07 does not represent the complete azimuthal average at $r \gtrsim 85''$, and thus the employed regularization can progressively bias the mass density high as $r$ increases.

5.3. Is the Cluster Galaxy Distribution Inconsistent with the Mass Profile of J07?

The current, well-accepted, structure formation paradigm postulates that galaxies are biased tracers of hosting dark matter. Gravitational lensing studies of galaxy clusters have demonstrated that even in clusters of complex morphology the spatial correlation between galaxies and dark matter is strong (e.g., Hoekstra et al. 2000; Jee et al. 2005; Clowe et al. 2006), although Mahdavi et al. (2007) recently claims that a puzzling counterexample is seen in Abell 520.

If galaxies and dark matter indeed follow each other, can we detect the ring-like structure of J07 in the cluster galaxy distribution? Of course, given that the ring-like structure of J07 has an only 5% contrast, it is impossible to detect the feature as an enhancement of galaxy number density around the "ring" even if we improve the statistics by azimuthally averaging the numbers. Figure 14 shows the projected number density of the cluster members as a function of radius (0.37 < $z$ < 0.41) obtained from the publicly available catalog of Moran et al. (2005), which extends the Czoske et al. (2001) catalog. The shot noise at $r \sim 75''$ is ∼45%, which is about nine times higher than the contrast; we did not correct for the completeness of the spectroscopic survey, which is negligible in this region compared with the shot noise.

Apart from the issue of detecting the ring-like structure of J07, it is still interesting to examine if the overall galaxy number density profile is consistent with the mass profile. As mentioned by J07, the mass profile at $r > 80''$ is measured from an incomplete circle. Therefore, in order to enable a fair comparison, we should limit the fitting range to $r \lesssim 80''$. The solid line in Figure 14 shows that the J07 mass profile is consistent with the galaxy distribution ($\chi^2$/d.o.f = 0.45) within $r \lesssim 80''$. When we instead try the fit with the data points at $r \lesssim 100''$, the result (dotted) is severely affected by the data at $r \gtrsim 80'', giving $\chi^2$/d.o.f = 1.92. Qin et al. (2008) used the latter comparison to argue that the galaxy distribution is inconsistent with the J07 mass profile. Because the mass profile of J07 at $r > 80''$ does not represent the azimuthal average, we do not agree with their interpretation.

How many galaxies do we need in order to detect the peculiar dark matter structure? Within the $r = 100''$ (80'') circle, there are 99 (84) 0.37 < $z$ < 0.42 galaxies in the Moran et al. (2005) catalog. The mass density at the $r \sim 75''$ bump is about 5% higher than the value at $r \sim 50''$. If we want to detect this rising mass density in the $50'' < r < 75''$ region with the galaxy distribution at the 2$\sigma$ level, we need ∼50 times more galaxies, which is even greater than the total number of objects (∼4000) detected in the ACS image. Our photo-$z$ analysis estimates that about 350 out of 4000 galaxies are in the redshift range 0.3 < $z$ < 0.5, and this number certainly does not help us to reveal the ring-like dark matter structure.

6. CONCLUSIONS

Our main results of the investigation of the ICL and intracluster medium (ICM) in the galaxy cluster Cl 0024+17 are summarized as follows.

1. The ICL profile closely resembles the peculiar dark matter structure reported in J07, which stops decreasing at $r \sim 50''$ (∼265 kpc) and slowly increases until it turns over at $r \sim 75''$ (∼397 kpc).
2. The feature is present in both ACS and Subaru images in nearly all available passband images with a significance in general higher in red filters.
3. The ICM profile shows a bump at $r \sim 60''$ (∼318 kpc). The radius of the ICM ring is ∼20% smaller than that of the dark matter ring.
4. The two-dimensional map of the diffuse light in the cluster shows that the ICL distribution is elongated toward northwest following cluster members.
5. The ICL color is consistent with the cluster red-sequence color at small radii ($r < 40''$), but becomes bluer for increasing radii.
6. The ICL fraction of Cl 0024+17 is \( \sim 28\% \) (\( \sim 37\% \)) in F775W and F850LP (F475W, F555W, F625W) without any strong indication of radial dependence. Considering the redshift of the cluster, these values are likely to be at the high end of the distribution.

These results not only support the presence of the peculiar dark matter structure of J07 revealed by coherent fluctuation of the background galaxy shapes across the \( r \sim 75'' \) circle, but also demonstrates the usefulness of the ICL as a powerful probe of dark matter substructure in galaxy clusters. Theoretically, however, it is still disputable whether or not the ICL distribution for a \( z = 0.4 \) cluster should reveal the underlying dark matter. Numerical simulations by Rudick et al. (2006) show that the ICL morphology is a strong function of time. At early epoch most intracluster stars reside in outer halos of individual galaxies while with time more tidal and filamentary structures develop. As the evolution progresses further, it is shown that these transitory features disappear into the more diffuse, common cluster halo. If we associate the redshift \( z = 0.4 \) with the young dynamical age in ICL evolution, it is difficult to understand why the cluster’s ICL follows the dark matter structure so remarkably well as shown in this work. On the other hand, if Cl 0024+17 is regarded as already dynamically mature based on its optical richness or mass, the similarity between the ICL and dark matter structures may not be surprising. The high ICL fraction of the cluster supports the possibility that Cl 0024+17 is already mature in the context of the ICL evolution. Alternatively, it is also plausible that the high-speed collision 1–2 Gyr ago might have liberated unusual amount of stars from the cluster galaxies.

The detection of the ICM bump at \( r \sim 60'' \) opens an important opportunity for the study of the dynamical interplay between the intracluster medium and the underlying dark matter. One simplistic scenario that one can make out of this feature is that both the ICM and dark matter ring-like structures have the same dynamical origin, and both rings (or shells) are expanding. In this case, the expansion of the ICM ring must lag behind the dark matter ring because of the ram pressure, which may explain the observed \( \sim 15'' \) (~80 kpc) offset.

In a recent dark matter only simulation, Zu Hone et al. (2009) claim that a bump can arise in cluster collisions only when the initial particle velocity distribution is circular, and the feature becomes a “shoulder” as the tangential anisotropy decreases. Our re-examination of the J07 collision simulation reveals that the initial orbits of the particles in the cluster core were indeed biased toward tangential anisotropy although the velocity anisotropy is not as extreme (i.e., circular) as shown by Zu Hone et al. (2009). As the distinction between “bump” and “shoulder” is whether or not the slope of the post-collision mass profile in the intermediate range (i.e., 50'' < \( r < 75'' \)) is positive, we believe that many other parameters such as the slope of the initial density profile, the fraction of the gas particles, the relative mass ratio/speed of the two subclusters, etc., should also be considered together with the initial distribution of the particle orbits in order to fully address the issue. Nevertheless, it is clear from the Zu Hone et al. (2009) simulation that the creation of the ring-like structure, if the high-speed collision is to be the cause as suggested by J07, requires some degree of tangential anisotropy at least in the core of the cluster.

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