In a galaxy cluster, galaxies are mostly collisionless particles in recent epochs. They resemble collisionless cold dark matter particles in some way. Therefore, the spatial distributions of dark matter and cluster galaxies might be expected to possess similar features in the gravitational potential of a cluster. Here we use the galaxy distribution in cluster Cl 0024+17 to probe for the ringlike dark matter structure recently discovered by means of strong and weak lensing observations. The galaxies are taken from the catalog of Czoske et al., which contains 650 objects with measured redshifts, of which ~300 galaxies have redshifts in the range $0.37 < z < 0.41$ (and are therefore probable cluster members). We find that, at about the 3 $\sigma$ level, the ringlike structure seen in the dark matter measurement is not observed in the projected two-dimensional galaxy distribution.

**ABSTRACT**

In a galaxy cluster, galaxies are mostly collisionless cold dark matter particles in recent way. Therefore, the spatial distributions of dark matter and cluster galaxies might be expected to possess similar features in the gravitational potential of a cluster. Here we use the galaxy distribution in cluster Cl 0024+17 to probe for the ringlike dark matter structure recently discovered by means of strong and weak lensing observations. The galaxies are taken from the catalog of Czoske et al., which contains 650 objects with measured redshifts, of which ~300 galaxies have redshifts in the range $0.37 < z < 0.41$ (and are therefore probable cluster members). We find that, at about the 3 $\sigma$ level, the ringlike structure seen in the dark matter measurement is not observed in the projected two-dimensional galaxy distribution.

**Subject headings:** cosmology: observations — dark matter — galaxies: clusters: individual (Cl 0024+17) — gravitational lensing — X-rays: galaxies: clusters

### 1. INTRODUCTION

The galaxy cluster Cl 0024+17 (at $z = 0.4$) has recently been reported, from strong and weak lensing observations, to have a ringlike dark matter structure. The radius of the ring was measured to be ~0.4 Mpc (Jee et al. 2007). This unique structure has been suggested as the result of a high-speed line-of-sight collision of two massive clusters ~1–2 Gyr ago. Ripples in the mass distribution that were not traced by the distribution of baryonic matter (i.e., the intracluster gas) provide strong evidence for the existence of dark matter. The same result has also been reached for other systems, e.g., the famous Bullet Cluster 1E 0657−56 (Markevitch et al. 2002; Clowe et al. 2004, 2006), clusters Cl 0152−1357 and MS 1054−0321 (Jee et al. 2005a, 2005b), and some other clusters (Shan et al. 2008). Hence, it would be of particular interest to test this unique ringlike dark matter structure by other means.

Galaxies in a cluster of galaxies are mostly collisionless particles. Their dynamical behavior is quite different from that of the intracluster gas but instead resembles collisionless cold dark matter particles in some way. Therefore, the galaxy distribution in a cluster could be expected to exhibit similar features to the dark matter distribution. This has been well demonstrated by the extreme case of the Bullet Cluster.

While the intracluster gas in cluster 1E 0657−56 has a rather prominent offset from the dark matter distribution, which has been used as direct evidence against modified Newtonian gravity (Milgrom 1983), the cluster galaxies, on the other hand, were found to trace the dark matter distribution remarkably well (Markevitch et al. 2002; Clowe et al. 2004, 2006). Similar results have also been found in other systems such as clusters Cl 0152−1357 and MS 1054−0321 (Jee et al. 2005a, 2005b).

These findings are the motivations for our attempts to investigate quantitatively the galaxy distribution in cluster Cl 0024+17, in order to probe for its reported ringlike structure of dark matter. If the galaxies exhibit similar features in their spatial distributions, then they may provide us an independent verification of the discovered dark matter ring.

The galaxy cluster Cl 0024+17 has been a target of a number of studies since its discovery (see Jee et al. 2007 for a historical review, and references therein). Czoske et al. (2001) have made a comprehensive study of the galaxies in this cluster, especially their redshift distribution. They have compiled a catalog from a wide-field CFHT/WHT survey that contains 650 objects with measured redshifts, of which 295 galaxies have redshifts in the range $0.37 < z < 0.41$ and are therefore probable cluster members.

Here we use the sample of 295 cluster galaxies from the Czoske et al. (2001) catalog and calculate, for each galaxy, the number density of the cluster galaxies as a function of their redshift distribution. They have compiled a catalog from a wide-field CFHT/WHT survey that contains 650 objects with measured redshifts, of which 295 galaxies have redshifts in the range $0.37 < z < 0.41$ and are therefore probable cluster members.

### 2. GALAXY DISTRIBUTION

The Czoske et al. (2001) catalog provides the redshifts and positions (right ascensions and declinations) of 650 objects in the Cl 0024+17 sky area. Following Jee et al. (2007), we choose the cluster center to be located at the geometric center of the “dark matter ring”, i.e., $\alpha_{2000.0} = 00^h26^m35.92^s$, $\delta_{2000.0} = 17^\circ09'35.5''$. We define the cluster axis to be the line of sight through the cluster center and the radial distance $r$ to be the angular distance of an object from the cluster axis. Then we calculate the value of $r$ for each of the 295 galaxies, from their right ascensions and declinations. For simplicity $r$ here is in units of arcseconds. In the $\Lambda$CDM cosmology with $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, and $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$ and at the cluster distance of $z = 0.395$, $1''$ corresponds to an angular diameter distance of about 5.28 kpc.

Numerical simulations have suggested that the collision of the two subclusters was along the line of sight, and the “dark matter ring” was also found to be along the line of sight. Thus, the configuration of the cluster is essentially two-dimensional and axisymmetric along the line of sight. As a result, we are able to treat the galaxy distribution as a two-dimensional problem. Assuming isotropy, we calculate the two-dimensional number density of the cluster galaxies as a function of $r$ only. If the galaxies trace the dark matter distribution, then a con-
centation of galaxies near $r = 75''$ (corresponding to ~0.4 Mpc) might be expected.

The results are presented in Figure 1. The two-dimensional number density of the 295 cluster galaxies is plotted as a function of $r$. The histogram shows the observed galaxy distribution, with statistical error bars in each bin computed using the Gaussian statistic approximation as

$$
\sigma_i = \frac{\sqrt{n(r)}}{\pi r_i (r_{i+1} - r_i)},
$$

where $n(r_i)$ is the number of galaxies in each bin and $r_i - r_{i+1}$ is the width of bin. We use a data bin of 5''. Following the dark matter profile of Jee et al. (2007), we plot as a dotted curve the "expected" galaxy distribution, if galaxies follow the dark matter distribution. The normalization of this curve is chosen such that both curves best fit the observed galaxy distribution. The best fit is obtained by minimizing the total $\chi^2$ for dark matter and galaxy distributions:

$$
\chi^2 = \sum_{i=1}^{n} \left[ \frac{k_{\text{DM}}(r_i) - \alpha k_{\text{Gal}}(r_i)}{\sigma} \right]^2,
$$

where $\alpha$ is the normalization factor and $k_{\text{DM}}$ and $k_{\text{Gal}}$ are the convergence from weak lensing observation and galaxy number density, respectively.

The position of the ring is marked by the vertical dashed line, i.e., at a radial distance of $r = 75''$. Figure 1 displays only the galaxy distribution within $r = 100''$ (or ~1 Mpc), in accordance with the dark matter profile range of Jee et al. (2007). Indeed, the dotted curve in Figure 1 cannot be used directly for comparison with the observed galaxy distribution, due to the selection biases caused by the completeness of the Czoske et al. (2001) catalog. The completeness of the sample varies with radius, from >80% at the cluster center to <50% in the outer regions. The contour lines in Figure 2 show the completeness variation (see also Fig. 7 in Czoske et al. 2001). Therefore, a completeness correction is needed to mimic a more "realistic" galaxy distribution, in order to compare with the actually observed galaxy distribution.

To do this, we obtain from the two-dimensional completeness contours an averaged completeness that varies with the cluster radius only (one-dimensional). To compute the average completeness, we simulate 100,000 galaxies for $r \leq 100''$, assuming galaxies follow dark matter. Each galaxy is then selected according to the completeness value at its position. The average radial completeness is computed as the observed number of galaxies in an $r$ bin divided by the number of simulated galaxies in the corresponding bin. Our expected galaxy distribution is then corrected from the dotted curve to the thick solid curve in Figure 1. The result of the completeness correction is that the bump in the dotted curve near $r = 75''$ has been slightly suppressed.

The new normalization factor $\alpha$ has been fitted by minimizing the $\chi^2$ for the whole region of $r \leq 100''$. The minimum is found to be $\chi^2 = 38.9$, with a number of degrees of freedom $N_{\text{gal}} = 19$. The confidence level of the fit is $\text{CL} = 0.64\%$. Such a low confidence level suggests an inconsistency between the dark matter and galaxy distributions. The dashed curve is obtained by fitting the normalization factor for $r \leq r_{\text{ring}} = 75''$. The $\chi^2$ is found to be equal to 7.7, with a number of degrees of freedom $N_{\text{gal}} = 13$ and a confidence level $\text{CL} = 9.4\%$, indicating a much better agreement between both distributions. We then estimate, for the dashed curve, the number of galaxies $\delta N_{\text{gal}}$ in the $r > r_{\text{ring}}$ regions in Figure 1 and compare it to observations. We find that $\delta N_{\text{gal}} = 22.0 \pm 7.5$, which suggests that, at a level of about 3 $\sigma$, the newly discovered ringlike struc-
ture of dark matter in Cl 0024+17 is not mimicked by the distribution of the galaxies in the cluster. Such a result is quite different from the case of the Bullet Cluster (Markevitch et al. 2002; Clowe et al. 2004, 2006) or clusters Cl 0152−1357 and MS 1054−0321 (Jee et al. 2005a, 2005b), where the galaxy distributions were found to trace the dark matter distributions well.

To estimate more precisely the confidence level of our probe of the ringlike dark matter structure using the observed galaxies, we have used a simulation of the cluster survey. For this purpose we extract the completeness curves from the Czoske et al. (2001) catalog. Galaxies have then been isotropically simulated according to the radial dark matter distribution and passed through completeness using a simple Metropolis method. Figure 2 shows a given Monte Carlo realization of a simulated survey.

Each simulated experiment is normalized with the observed 72 galaxies within the dark matter ring randomized using the Poisson statistics. An experiment is accepted if the number of simulated galaxies inside the ring is smaller than or equal to the number of actually observed galaxies (17 galaxies). The confidence level exclusion is computed as one minus the number of accepted experiments divided by the total number of simulated experiments. Using 10,000 simulated experiments, we find a confidence level exclusion of 99.6%, which confirms our previous analysis.

3. CONCLUSION AND DISCUSSION

Unlike the intracluster gas, galaxies in a cluster of galaxies are mostly collisionless particles. Their dynamical properties resemble the properties of dark matter to some extent. Therefore, under the same gravitational potential of a cluster, one may expect to find similar features between dark matter and galaxy distributions. In this respect, galaxy distribution might be used to probe dark matter distribution, especially for rich clusters.

Indeed, the bump at $r \sim 75''$ in the mass density profile of Jee et al. (2007), which gives rise to the reported dark matter ring, is a quite remarkable feature. An increase in galaxy number density at $r \sim 75''$ should be expected in Figure 1, if galaxies trace dark matter. Unfortunately, at the 3 $\sigma$ level, cluster Cl 0024+17 does not appear to exhibit the level of consistency between dark matter and galaxy distributions that have been found in other clusters such as the Bullet Cluster, Cl 0152−1357, and MS 1054−0321.

The reason for this inconsistency could be that the sample of 295 galaxies is not large enough for a stringent constraint, and the galaxies are too sparsely distributed within the radius of $\sim 1$ Mpc. We have realized this disadvantage. Fortunately, the axisymmetrical configuration of the system along the line of sight allows us to plot the surface density of the galaxies as a function of radius $r$ only. This has greatly increased the number of galaxies in each bin of our Figure 1 and hence improved the quality of our data. We have also tried different bin sizes but reached similar results. Our simulation has been found to be insensitive to the above effects and confirms our 3 $\sigma$ confidence level.

It should be noted that the completeness given by Czoske et al. (2001) has presumably been smoothed over an area comparable to or larger than the width of the dark matter ring. This could reduce the contrast in galaxy number density that we derived from the completeness correction. However, if the completeness does not vary drastically around the position of the ring, this may not lead to a significant change in our result.

The inconsistency could also be because, as argued by Jee et al. (2007), the density contrast in the ringlike structure is low. But, however, compared to a pure NFW distribution (Navarro, Frenk, & White 1997) where the dark matter density decreases rapidly and monotonically with radius, the bump at $r \sim 75''$ as shown in the dark matter density profile of Jee et al. (2007) is still quite prominent. This prominent feature, if it really exists, might be “seen” if we had enough luminous “tracers” of dark matter (e.g., the cluster galaxies). Interestingly, a recent study has shown that ringlike artefacts could be produced in lens reconstructions (Liesenborgs et al. 2008).

Nevertheless, as has been demonstrated in this Letter, the galaxy spatial distribution in a cluster of galaxies could provide a useful and complementary tool for our study of the dark matter distribution, due to the similarities in the collisionless nature of cluster galaxies and cold dark matter particles. This would be of particular interest for rich clusters of galaxies.

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