DISCOVERY OF X-RAY EMISSION FROM THE DISTANT LENSING CLUSTER OF GALAXIES
Cl 2236 — 04 AT z = 0.552

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ABSTRACT

X-ray emission from the distant lensing cluster Cl 2236 — 04 at z = 0.552 was discovered by ASCA and ROSAT/HRI observations. If the spherical symmetric mass distribution model of the cluster is assumed, the lensing estimate of the cluster mass is a factor of 2 higher than that obtained from X-ray observations as reported for many distant clusters. However, the elliptical and clumpy lens model proposed by Kneib and coworkers is surprisingly consistent with the X-ray observations, assuming that the X-ray-emitting hot gas is isothermal and in a hydrostatic equilibrium state. The existence of the cooling flow in the central region of the cluster is indicated by the short central cooling time and the excess flux detected by ROSAT/HRI compared to the ASCA flux. However, it is shown that, even if the Cl 2236 — 04 has a cooling flow in the central region, the temperature measured by ASCA, which is the mean emission-weighted cluster temperature in this case, should not be different from the virial temperature of the cluster. Therefore, we conclude that the effects of the clumpiness and nonzero ellipticity in the mass distribution of the cluster are essential to explain the observed features of the giant luminous arc, and in this cluster there is no discrepancy between strong lensing and X-ray estimation of the cluster mass.

Subject headings: galaxies: clusters: individual (Cl 2236 — 04) — gravitational lensing — X-rays: galaxies

1. INTRODUCTION

It is one of the prime objectives in observational cosmology to determine mass distributions and total masses of clusters of galaxies at various redshifts. It provides a clue to constrain the unknown cosmological parameters: the species of dark matter, the nature of cosmological mass density fluctuations, the average density in the universe, and the cosmological constant.

Recently, gravitational lensing has become a powerful tool to measure the mass distribution in clusters. Strong lensing events, such as multiple images and/or giant luminous arcs, make it possible to model the central region of clusters. However, many clusters show a mass discrepancy with a total mass deduced from a strong lensing observation being larger by a factor of 2 — 3 than that deduced from X-ray observations (Loeb & Mao 1994; Miralda-Escudé & Babul et al. 1995; Kneib et al. 1995; Schindler et al. 1995, 1997; Wu & Fang 1997; Ota, Mitsuda, Fukazawa 1998). However, there are some clusters whose masses deduced in these two ways agree very well. In such cases, the multiphase of the intracluster gas (Allen, Fabian, & Kneib 1996; Allen 1998) or asymmetric mass distribution (Pierre et al. 1996; Böhringer et al. 1998) has been taken into account in the lens modeling. This indicates that careful studies for a large number of clusters are necessary before reaching the conclusion that the lens modeling gives higher mass estimation than that from X-rays.

Cl 2236 — 04 was discovered by Melnick et al. (1993) with a giant luminous arc. The redshift of the arc was measured to be zarc = 1.116 (Melnick et al. 1993), confirming the gravitational lens picture very satisfactorily. The arc is rather straight, and a velocity structure across the arc is measured (Melnick et al. 1993). These factors give strict constraints on the lensing mass estimation. Further, Cl 2236 — 04 is one of the best and rarest clusters at high redshift of z > 0.5 for which comparison of the mass distribution deduced by two individual methods is possible. We have performed the first deep ASCA and ROSAT/HRI pointing observations toward Cl 2236 — 04. In this paper, we report the discovery and the properties of X-ray emission from Cl 2236 — 04, and the mass distribution deduced from the X-ray observation is compared to the lensing mass.

2. X-RAY OBSERVATIONS

2.1. ASCA Observation

We performed an ASCA observation of Cl 2236 — 04 in 1995 June with an effective exposure time of about 40 ks. A new X-ray source was discovered in the direction of Cl 2236 — 04 with more than 10 σ significance (hereafter referred to as AX J2239 — 0429). The X-ray source count rate is 4 × 10^-3 counts s^-1 for each gas imaging spectrometer (GIS) and 6 × 10^-3 counts s^-1 for each solid imaging spectrometer (SIS). The X-ray peak position of the source is (z, δ) = (22h39m32.3s, -44°30′) (J2000). This is consistent with the position of the cD galaxy, (z, δ) = (22h39m32.7s, -44°29′24″) within the ASCA position determination accuracy of (Δz, Δδ) = (±4″, ±1″).

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Figure 1 shows the X-ray spectra of AX J2239—0429 obtained by ASCA. The ASCA observatory has four identical telescopes covering the energy range of 0.3–10 keV (Tanaka et al. 1994). They are equipped with two gas imaging spectrometers (GIS 2 and 3) and two solid imaging spectrometers (SIS 0 and 1) at the focal plane. The solid lines are the best-fit Raymond-Smith models obtained by simultaneous fitting of the GIS and SIS spectra.

The background-subtracted radial profile of AX J2239—0429 obtained by ROSAT/HRI. The radial profile is fitted to a so-called isothermal β model:

\[ S(\theta) = S_0 \left( 1 + \frac{\theta^2}{\theta_c^2} \right)^{-3\beta+1/2}, \]

where \( \theta_c \) is angular core radius; best-fit parameters are summarized in Table 3. The source is clearly more extended than the PSF profile. Therefore, we conclude that AX J2239—0429 is X-ray emission from the cluster of galaxies Cl 2236—04. This is the first X-ray detection from the cluster. Because redshift measurement has been done only for a few member galaxies, the X-ray detection confirms that Cl 2236—04 is a real, gravitationally-bound entity. In Table 4, the total gas mass and the total gravitational mass as calculated below are summarized. The gas mass fraction is a typical value.

The central electron number density gives a cooling time of 3.6 Gyr (from eq. [5.23] of Sarazin 1986), which is about half the age of the universe at \( z = 0.552 \). This short cooling time and the higher count rate of ROSAT/HRI compared to ASCA may be a signature of cooling flow. The cooling radius where the cooling time equals the age of the universe

| \( k_B T \) (keV) | \( Z_F \) (\( Z_\odot \)) | \( N_H \) (\( 10^{20} \) cm\(^{-2} \)) | \( \beta \) | \( \chi^2 \) per Degree of Freedom |
|-----------------|-----------------|-----------------|-----|-----------------|
| 6.2 +1.6/−1.1 | 0.0 +0.38/−0.0 | 3.87* | 0.552* | 72.66/80 = 0.94 |

* Fixed.

| Photon Index | \( N_H \) (\( 10^{20} \) cm\(^{-2} \)) | \( \chi^2 \) per Degree of Freedom |
|-------------|-----------------|-----------------|
| 1.81 +0.15/−0.15 | 3.87* | 75.00/80 = 0.96 |

* Fixed.
at $z = 0.552$ is $\sim 10.6 = 78.4$ kpc. About 30% of the total emission detected by HRI is coming from the region within this cooling radius. Since the extent of the cooling flow is too small for the ASCA PSF to resolve the cooling flow region, and the photon statistics of the ASCA spectra of AX J2239–0429 are too poor to introduce any further parameters, the current ASCA spectra cannot constrain the cooling flow model.

### 3. COMPARISON WITH LENS MODELS

#### 3.1. Spherically Symmetric Lens Model

First, we examine whether the cluster can be modeled by a spherically symmetric mass distribution. Assuming that the X-ray-emitting hot gas is isothermal and in hydrostatic equilibrium, the hydrostatic equilibrium equation gives the cluster mass contained within a radius $r$:

### TABLE 4

| Parameter | $0.6 \, h_{50}^{-1}$ Mpc | $1.0 \, h_{50}^{-1}$ Mpc |
|-----------|--------------------------|--------------------------|
| $n_e \, (h_{50}^{-1}\, \text{cm}^{-3})$ | $2.44 \times 10^{-2}$ | $2.44 \times 10^{-2}$ |
| $M_{\text{gas}} \, (h_{50}^{-5/2} \, M_\odot)$ | $3.26 \times 10^{13}$ | $5.76 \times 10^{13}$ |
| $M_{\text{grav}} \, (h_{50}^{-5/2} \, M_\odot)$ | $2.69 \times 10^{14}$ | $4.39 \times 10^{14}$ |
| $M_{\text{gas}} / M_{\text{grav}} \, (h_{50}^{-5/2})$ | 0.12 | 0.13 |
where $k$ is the spherical isothermal cosmic abundance. Hereafter this model is referred to as the spherical isothermal model. The lens equation for this mass distribution is

$$M(r) = \frac{kT}{G\mu m_h} \frac{3\beta}{r_c^3} \frac{1}{1 + (r/r_c)^2}, \quad (2)$$

where $\mu = 1.3/2.1$ is the mean molecular weight for gas of cosmic abundance. Hereafter this model is referred to as the spherical isothermal $\beta$ model. The lens equation for this mass distribution is

$$\hat{\theta}_s = \hat{\theta}_l - D \sqrt{\hat{\theta}_l^2 + 1}, \quad (3)$$

where

$$D = \frac{6\pi \beta}{\theta_c} \frac{kT}{\mu m_h c^2} D_{LS}, \quad (4)$$

$\hat{\theta}_s(\hat{\theta}_l)$ is the angle between the lens and the source (image) in units of $\theta_c$, and $D_{LS}(D_{OS})$ is the angular diameter distance between the lens (the observer) and the source (the explicit expression is given in Fukugita et al. 1992). The value $D$ is called the lens parameter and determines the efficiency of the lens. When $D \leq 1$, the lens always produces a single image, and image deformation is small. On the other hand, when $D > 1$, equation (2) has three routes for $\hat{\theta}_s = 0$, such as

$$\hat{\theta}_l = 0, \pm \sqrt{D^2 - 1}, \quad (5)$$

and an infinitely amplified circular image is formed with a radius of $(D^2 - 1)^{-1/2} \theta_c$, which is called the Einstein ring radius. The tangentially stretched giant luminous arc is formed near the tangential critical line in a spherical symmetric lens model. Therefore, a separation between the giant luminous arc and the center of the cluster must be close to the Einstein ring radius. Assuming that the giant luminous arc in Cl 2236—04 appears at the Einstein ring radius, the temperature and core radius measured by X-ray observations are compared in Figure 4 to a relation of those parameters required to explain the existence of the giant luminous arc at the observed position. If the universe does not contain a cosmological constant, a mass distribution model derived from X-ray observations with a spherical isothermal $\beta$ model cannot explain the existence of the giant luminous arc at the observed position, even if 90% one-parameter errors in temperature and core radius are taken into account. The observation of the giant luminous arc requires a higher temperature and smaller core radius; that is, it requires a stronger mass concentration in the cluster than that derived from the X-ray observations. As shown in Figure 4, an introduction of a cosmological constant implies that a smaller mass concentration is able to reproduce the same Einstein ring radius compared to a zero cosmological constant model (e.g., Hamana et al. 1997). The temperature and core radius relation derived from the giant luminous arc position with $\hat{\theta}_l = (0.1, 0)$ has an overlapping region with a 90% error box obtained by X-ray observations.

3.2. Nonspherical and Clumpy Lens Model

There are several pieces of evidence indicating that deviations of the mass distribution in Cl 2236—04 from spherical symmetry are playing a significant role in the formation of the observed giant luminous arc. First of all, the almost straight nature of the giant luminous arc and the fact that no counterimage candidate has been found, in spite of a deep and wide field search (Kneib, Melnick, & Gopal-Krishna 1994, hereafter KMG), cannot be explained by a fold arc produced by a spherical symmetric lens. It implies either an elliptical or a substructural nature of the lens (Narasimha & Chitre 1993; KMG). Second, the X-ray morphology shows a clear deviation from a circular symmetry.
and elongation in the northeast-southwest direction. Finally, there is a giant galaxy very close to the giant luminous arc, and a lensing effect by this galaxy should not be negligible.

Currently, the lens model proposed by KMG is the only successful model that is consistent with observed lensed image features. The model assumes two clumps of mass in this cluster. It predicts that the core radius \(r_c\) and the one-dimensional central velocity dispersion \((\sigma_0)\) for the two clumps are \(r_c = 7''\) (52.56 kpc) and \(\sigma_0 = 610\) km \(s^{-1}\) for the clump centered on the cD galaxy and \(r_c = 3''\) (22.10 kpc) and \(\sigma_0 = 390\) km \(s^{-1}\) for the clump centered on the second giant galaxy in the cluster, where \(H_0 = 50\) km \(s^{-1}\) Mpc \(^{-1}\) and \(\Omega_0 = 1\). The iso-mass densities of this model are shown in Figure 6 in KMG (note that south is up in the figure).

If a hydrostatic distribution for the X-ray-emitting gas is assumed (for validity of this assumption see, e.g., Schindler 1996), this lens mass model can be directly tested by X-ray observations. First of all, the coincidence between the X-ray peak and the cD center indicates that the center of cluster gravitational potential coincides with the cD position, as predicted by KMG. The core radius predicted by KMG is consistent with the ROSAT/HRI result within errors. The position angle of the X-ray image surprisingly coincides with the prediction of KMG. In the northern part of the cD galaxy, the direction of the major axis of the X-ray image is tilted northward. It might be evidence of a substructure in this direction (Neumann & Böhringer 1997), and it is roughly consistent with the position of the substructure predicted by KMG. In the limit of zero ellipticity, the lens equation of the cluster adopted by KMG (Mellier, Fort, & Kneib 1993) has the same functional form as equation (3). Since \(\frac{\beta(kT/\mu m_0)}{\theta_e}\) in equation (3) \((\approx 5.5 \times 10^{14}\) cm \(^2\) s\(^{-2}\) arcsec \(^{-4}\)) and the measured core radius are almost the same as \(\sigma_0/r_c\) in the KMG model \((\sim 5.3 \times 10^{14}\) cm \(^2\) s\(^{-2}\) arcsec \(^{-4}\)) and KMG’s core radius within the errors, the potential depth of the KMG model of cluster mass distribution is consistent with that inferred from the X-ray observations under assumptions of isothermal and hydrostatic equilibrium. In Figure 3, the best-fitting surface brightness model is shown, assuming that the hot gas is isothermal— with the best results for ASCA (dashed line) and the 90% lower limit for ASCA (dashed-dotted line)—and hydrostatic in the gravitational potential of the KMG model cluster with zero ellipticity and no substructure. In this fitting, only the central surface brightness is treated as a free-fitting parameter. Note that the three-dimensional cluster mass distribution is deduced as shown in Mellier et al. (1993) in this procedure. Although the model profile with the best-fit temperature is too flat, the profile with the 90% lower limit temperature gives a reasonably good fit, where the fitting result yields a \(\chi^2\) per degree of freedom of 73.65/59 = 1.25. These results show that the KMG model is surprisingly consistent with the results of the X-ray observations.

4. DISCUSSIONS AND CONCLUSION

A new X-ray source in the direction of the distant lensing cluster, Cl 2236−04, is discovered by ASCA, named AX J2239−0429. The source extent is resolved by the following ROSAT/HRI observation, and it confirms that the X-ray source is the galaxy cluster Cl 2236−04.

The mass distribution of the cluster derived by X-ray observations and that derived by the observed nature of the giant luminous arc are compared. It is found that within the framework of a spherical isothermal \(\beta\) model, the mass required to explain the observed location of the giant luminous arc is larger than that expected from the X-ray observations, as reported for many giant luminous arc clusters (Wu & Fang 1997). An introduction of a large cosmological constant reduces the lensing mass, but the total reduction is only 20%−30%. Therefore, the cosmological constant cannot be the main solution for the discrepancy found in many clusters.

Cooling flow can be one of the other possible solutions (Allen et al. 1996; Allen 1998). According to the cooling flow model, the hot gas in the cluster central region is in the multitemperature phase. The temperature of the hottest phase gas, which represents a real gravitational potential depth, obtained by the multiphase model fitting becomes much higher than the temperature obtained by the single-phase model fitting, because the latter is the average temperature of the multitemperature gas. Allen (1998) claims that most of the discrepancy reported before can be explained by the existence of the cooling flow. There is much evidence of the existence of the cooling flow in the central region of AX J2239−0429, as shown in § 2. It may be possible that the measured temperature of AX J2239−0429 underestimates the cluster potential depth. If the ASCA temperature underestimates the cluster potential depth by a factor of 2 because of the cooling flow, the Einstein ring radius of the cluster for a source at \(z = 1.116\) becomes as large as the distance between the giant luminous arc and the cluster center. However, the straight nature of the arc and the lack of a bright counterimage cannot be explained by a spherically symmetric lens. Further, the perturbation by the gravitational potential of galaxy A is not negligible. The absolute luminosity of galaxy A in the visual band is \(3.3 \times 10^{11}\) \(L_\odot\) (Melnick et al. 1993). This luminosity is translated into the line-of-sight velocity dispersion of \(\sim 370\) km \(s^{-1}\) by using the Faber-Jackson law (Binney & Tremaine 1987). If the potential depth is about a factor of 2 deeper than that inferred from the ASCA temperature, it is impossible to construct a model that is able to explain the location and the observed feature of the giant luminous arc because of the large perturbation of the galaxy A. Therefore we conclude that, even if the AX J2239−0429 has a cooling flow in the central region, the temperature measured by ASCA, which is the mean emission-weighted cluster temperature in this case, should not be different from the virial temperature of the cluster.

The most plausible solution is the effect of the clumpiness of the gravitational potential due to galaxy A and the nonzero ellipticity in the mass distribution of the cluster. KMG proposed the cluster mass distribution model by taking into account these effects, which explain the observed features of the giant luminous arc. The ellipticity, position angle, and velocity dispersion of the cluster predicted by KMG are surprisingly consistent with the results of the X-ray observations of the cluster, as shown in the previous section. The velocity dispersion of galaxy A assumed by KMG is also consistent with that deduced by the Faber-Jackson law. Therefore we conclude that the effect of the clumpiness of the gravitational potential due to galaxy A and the nonzero ellipticity in the mass distribution of the cluster are essential to explain the observed feature of the giant luminous arc, and the cluster mass distribution required by the strong lensing effect is totally consistent
with the X-ray observations, assuming that the X-ray-emitting hot gas is isothermal and in a hydrostatic equilibrium state.

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