

X-RAY OVERLUMINOUS ELLIPTICAL GALAXIES: A NEW CLASS OF MASS CONCENTRATIONS IN THE UNIVERSE?

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ABSTRACT

We detect four isolated, X-ray overluminous [$L_x > 2 \times 10^{43} (h/0.5)^{-2} \text{ ergs s}^{-1}$] elliptical galaxies (OLEGs) in our 160 deg² *ROSAT* PSPC survey. The extent of their X-ray emission, total X-ray luminosity, total mass, and mass of the hot gas in these systems corresponds to poor clusters, and the optical luminosity of the central galaxies ($M_R < -22.5 + 5 \log h$) is comparable to that of cluster cD galaxies. However, there are no detectable fainter galaxy concentrations around the central elliptical galaxy. The estimated mass-to-light ratio within the radius of detectable X-ray emission is in the range of 250–450 $M_\odot/L_\odot$, which is 2–3 times higher than typically found in clusters or groups. These objects can be the result of galaxy merging within a group. OLEGs must have been undisturbed for a very long time, which makes them the ultimate examples of systems in hydrostatic equilibrium. The number density of OLEGs is $n = 2.4^{+3.1}_{-1.2} \times 10^{-7} (h/0.5)^{-3} \text{ Mpc}^{-3}$ at the 90% confidence level. They comprise 20% of all clusters and groups of comparable X-ray luminosity, and nearly all field galaxies brighter than $M_R = -22.5$. The estimated contribution of OLEGs to the total mass density in the universe is close to that of $T > 7 \text{ keV}$ clusters.

Subject headings: cosmology: observations — dark matter — galaxies: clusters: general — X-rays: galaxies

1. INTRODUCTION

Large concentrations of matter in the universe are found using optical galaxies as tracers of mass. Systems with a wide range of mass and size were discovered by this technique, from pairs and triplets of galaxies to filaments extending for hundreds of megaparsecs. Do optical galaxy surveys detect all large-scale mass concentrations, or do there exist populations of “dark” massive objects?

X-ray surveys provide a method of finding compact, massive, optically dark objects because such objects are likely to contain gravitationally heated X-ray-emitting gas. Tucker, Tananbaum, & Remillard (1995) did not find any completely dark X-ray clusters in the *Einstein* data. However, X-ray surveys with *ROSAT* did find a new class of objects that could not be discovered optically—bright isolated elliptical galaxies surrounded by dark matter and hot gas halos typical of a group or a poor cluster. The first such object was a “fossil group” found by Ponman et al. (1994). The object appears optically as a giant isolated elliptical galaxy. Its X-ray halo extends for at least 500 kpc; such an extent implies the grouplike total mass. Böhringer et al. (1998) mention the existence of similar objects in the *ROSAT* All-Sky Survey. An X-ray observation of an optically selected isolated elliptical galaxy revealed the existence of a grouplike X-ray halo (Mulchaey & Zabludoff 1999).

Our large-area *ROSAT* survey of extended X-ray sources (Vikhlinin et al. 1998, hereafter Paper I) is ideal for the search for optically dark clusters and groups at low redshift. In this Letter, we report a detection of four objects similar to the Ponman et al. fossil group. We call them X-ray overluminous

elliptical galaxies (OLEGs). We show that these objects have gas and dark matter halos extending up to radii of 1 Mpc; they are more numerous and massive than was previously appreciated and represent an important class of mass concentrations in the universe.

We use $h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1} = 0.5$, except where the h -dependence is explicitly given, and $q_0 = 0.5$. All uncertainties are reported as 68% confidence intervals.

2. SAMPLE AND OVERALL X-RAY AND OPTICAL PROPERTIES

The R - and V -band optical CCD images of extended X-ray sources from our catalog (Paper I) were obtained on the FLWO 1.2 m and Danish 1.54 m telescopes. We examined these images and selected those objects that were obviously associated with a bright elliptical galaxy but had no corresponding concentration of fainter galaxies. To add confidence to this selection, two additional criteria were applied. First, the central galaxy redshift was required to be $z < 0.2$ because galaxy concentration is harder to detect in more distant objects. Second, we required the 0.5–2 keV X-ray luminosity to be $L_x > 2 \times 10^{43} \text{ ergs s}^{-1}$. This luminosity corresponds to poor Abell clusters that should be visible as galaxy concentrations in our CCD images. Fainter X-ray objects can be poor groups, and therefore we could misidentify them with single, isolated galaxies. These selections resulted in a sample of four objects (Table 1).

Two of them, 1159+5531 and 2114–6800, were previously detected in the *Einstein* surveys (Stocke et al. 1991 and Griffiths et al. 1992, respectively) and identified with normal elliptical galaxies. We also rediscovered the Ponman et al. (1994) object, 1340+4017. The remaining object, 2247+0337, first appears in our sample. We have measured the redshift of 2247+0337 and adopted the redshifts of others from the literature. There are several other plausible OLEG candidates; however, they do not satisfy either the redshift or the X-ray luminosity criteria.

In all four objects, the X-ray emission is detected with 2–3 σ significance out to a large radius of $R_x = 0.5$ –1 Mpc (Table 1). The X-ray surface brightness distribution shows no significant deviations from azimuthal symmetry in all objects

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TABLE 1
X-RAY AND OPTICAL PROPERTIES OF OLEGs

Object	z	L_x (ergs s $^{-1}$)	r_c^a (kpc)	R_x^b (kpc)	T^{est} (keV)	$t_{\text{cool}}^{\text{cool}}$ (yr)	$M_{\text{tot}}^{\text{est}}$ ($M_{\odot}$)	$M_{\text{gas}}^{\text{est}}$ ($M_{\odot}$)	L_{opt} ($L_{\odot}$)	M/L ($M_{\odot}/L_{\odot}$)
1159+5531	0.081	2.2×10^{43}	50	1000	2.2	2.0×10^9	1.6×10^{14}	9.2×10^{12}	4.6×10^{11}	347
1340+4017	0.171	2.5×10^{43}	71	500	2.3	3.3×10^9	8.3×10^{13}	4.8×10^{12}	3.1×10^{11}	267
2114-6800	0.130	2.0×10^{43}	61	600	2.1	2.1×10^9	9.2×10^{13}	5.1×10^{12}	2.7×10^{11}	340
2247+0337	0.199	4.1×10^{43}	194	850	2.8	1.2×10^{10}	1.7×10^{14}	1.6×10^{13}	4.0×10^{11}	425

NOTE.—Masses are estimated within R_x . Optical luminosities are measured in the R band within the same radius.

^a X-ray core radius.

^b The radius of detectable X-ray emission.

except for 1340+4017, which is elongated (Ponman et al. 1994).

Our optical images cover an area large enough to observe the entire X-ray-emitting region and to determine the local density of background galaxies. We have measured the optical luminosity by co-adding light from the central galaxy and all fainter galaxies within R_x and subtracting the estimated background contribution. The resulting R -band luminosities (with K -correction and extinction correction applied) are in the range of $(2.7\text{--}4.6) \times 10^{11} L_{\odot}$. These values are uncertain by $\approx 25\%$ because of the presence of relatively bright foreground or background galaxies. In all objects, at least 70% of light (excluding the background) comes from the central galaxy; the contribution from other galaxies does not exceed the level of background fluctuations.

3. PROPERTIES OF 1159+5531

Although this object was discovered by *Einstein*, its large X-ray extent remained unnoticed prior to the *ROSAT* observation. The long *ROSAT* exposure and the low background made it possible to trace the diffuse X-ray emission to a large radius and even perform a simple spectral analysis. The optical and X-ray properties of 1159+5531 appear to be representative of the other objects in our sample, and the main conclusions

derived from the 1159+5531 data can be applied to the entire OLEG population.

The X-ray contour map of 1159+5531 that is overlaid on the optical CCD image is shown in Figure 1. The X-ray surface brightness profile is shown in the top panel of Figure 2. The surface brightness is detected to 1 Mpc with $\approx 3\sigma$ significance. The β -model fit (Cavaliere & Fusco-Femiano 1976) in the entire radial range yields $\beta = 0.61$ and a small core-radius value $r_c = 43$ kpc. The central gas density derived from this fit corresponds to the gas cooling time $t_{\text{cool}} = 2 \times 10^9$ yr, indicating the presence of the cooling flow. Outside the central 200 kpc region, where the surface brightness is unaffected by enhanced cooling flow emission, the best-fit β -model yields $r_c = 400 \pm 185$ kpc and $\beta = 0.9 \pm 0.4$. The large uncertainties arise from the interplay between r_c and β . However, the gas and total mass at large radius depend mostly on the slope of the surface brightness profile, which is well constrained—a power-law fit, $S \propto r^{-\gamma}$, between 600 and 3000 kpc yields $\gamma = 3.6 \pm 0.6$.

The bottom panel of Figure 2 presents the gas temperatures in four annuli measured by fitting the *ROSAT* spectrum with the Raymond & Smith (1977) model. We fixed the metal abundance at 0.3 of the solar value and the Galactic hydrogen column at $N_{\text{H}} = 1.4 \times 10^{20} \text{ cm}^{-2}$ derived from the radio surveys

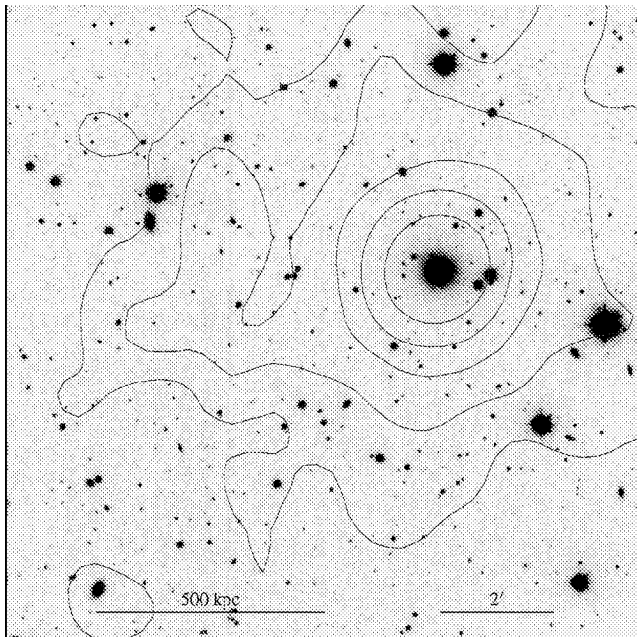


FIG. 1.— R -band CCD image of 1159+5531. The outer X-ray contour is approximately 800 kpc from the galaxy. Other bright objects are stars.

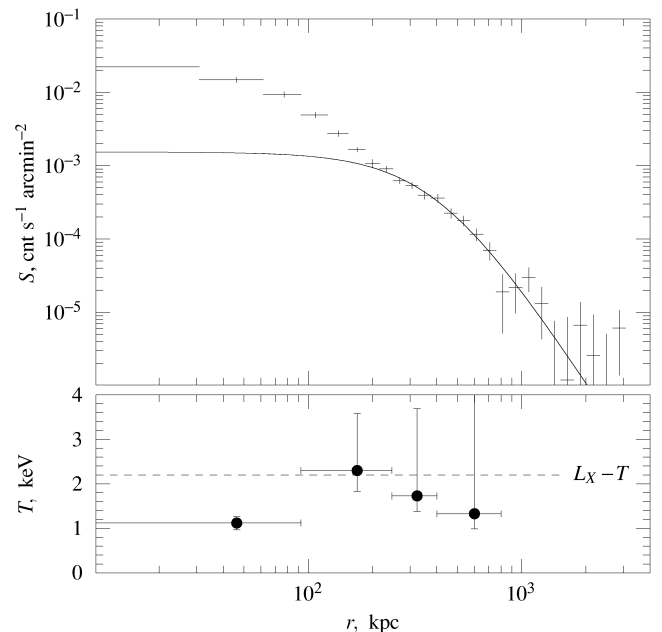


FIG. 2.—*ROSAT* PSPC X-ray surface brightness profile and temperature profile of 1159+5531. The solid line represents the β -model fit obtained by excluding the central 200 kpc affected by the cooling flow.

(Stark et al. 1992). Fitting to the overall *ROSAT* spectrum with free absorption yielded a consistent value, $N_{\text{H}} = (1.5 \pm 0.4) \times 10^{20} \text{ cm}^{-2}$. Within 100 kpc, the temperature is significantly lower than in the 100–250 kpc annulus, confirming the existence of the cooling flow. Temperatures are poorly constrained beyond 250 kpc because of low statistics and because *ROSAT* is insensitive above 2 keV; nevertheless, the lower limits show that the temperature does not drop below 1 keV to at least 800 kpc from the center. The temperature $T = 2.25 \text{ keV}$ derived from the L_x - T correlation for 1–3 keV clusters and groups (Fukazawa 1997; Hwang et al. 1999) is consistent with the spectral fit outside the cooling flow region. We will use this value for the mass calculations below.

The gas mass was calculated by deprojection of the observed X-ray surface brightness profile (Fabian et al. 1981). The total mass was derived from the hydrostatic equilibrium equation assuming constant temperature at all radii:

$$M(< R_x) = 1.1 \times 10^{14} M_{\odot} T_{\text{keV}} \beta R_x^3 / (R_x^2 + r_c^2), \quad (1)$$

where radii are in units of megaparsecs. The results of the mass determination at several radii are presented in Table 2. The formal statistical uncertainty of the total mass is 30%–40%, including uncertainties both in the slope of the surface brightness profile and in the overall temperature. At all radii, hot gas contributes 7%–8% of the mass. This is a factor of ~ 2 smaller fraction than in hot clusters but is comparable to the gas fraction in groups (David, Forman, & Jones 1995).

Optically, 1159+5531 appears as an isolated giant elliptical galaxy residing at the peak of the X-ray emission (Fig. 1). The sensitivity limit of this image corresponds to absolute magnitude $M_R = -14.8 + 5 \log h$ at the object redshift. Above this sensitivity limit, we detect 18 galaxies within a projected distance of 100 kpc from the central galaxy, while 15 ± 4 are expected because of the background estimated beyond 1 Mpc.

To measure the total optical luminosity, we integrated the light within 90 kpc of the central galaxy and within 15 kpc of fainter galaxies. We excluded the objects with peak surface brightness exceeding that of the central galaxy; the radial profiles of excluded objects show that all were stars. The light density due to background galaxies was measured outside a projected distance of 1 Mpc from the central galaxy. The optical luminosities within 0.4, 0.7, and 1 Mpc with the subtracted background contribution are reported in Table 2.

The optical properties of the central galaxy itself are remarkable. The diffuse optical light can be traced to $\approx 150 \text{ kpc}$ in R , V , and B bands. The light profile very accurately follows the de Vaucouleurs law with an effective radius $r_e = 16 \text{ kpc}$; there is no extended optical envelope as in cluster cD galaxies. The absolute magnitude is $M_R = -23.1 + 5 \log h$ and $M_V = -22.5 + 5 \log h$ (with K -correction and Galactic extinction correction applied). Such a high luminosity is rare in field elliptical galaxies but is typical of cD galaxies in clusters (Hoesel 1980). To summarize, 1159+5531 is an object with X-ray properties typical of poor clusters, and it contains an isolated galaxy whose optical luminosity resembles central cluster galaxies.

4. CRUDE MASS ESTIMATES IN OTHER OBJECTS

A detailed surface brightness analysis and spectral fitting could be performed only with the 1159+5531 data. In the remaining three objects, only crude estimates of the total and gas mass are possible. To control the accuracy of these esti-

TABLE 2
TOTAL MASS, GAS MASS, AND OPTICAL LUMINOSITY OF 1159+5531

Radius (kpc)	M_{tot} ($M_{\odot}$)	M_{gas} ($M_{\odot}$)	L_{opt} ($L_{\odot}$)	M_{tot}/L ($M_{\odot}/L_{\odot}$)	f_{gas}
400	4.6×10^{13}	3.9×10^{12}	4.2×10^{11}	110	0.08
700	1.2×10^{14}	1.0×10^{13}	4.4×10^{11}	270	0.08
1000	2.0×10^{14}	1.4×10^{13}	4.6×10^{11}	435	0.07

mates, we apply them to 1159+5531 also. The gas temperature is estimated from the L_x - T correlation (Fukazawa 1997; Hwang et al. 1999). The temperature scatter around the mean L_x - T relation is only $\approx 25\%$, which is accurate enough for our purposes. Additional confidence is added by the agreement of the L_x - T temperature estimate and the direct spectral fit in 1159+5531. The X-ray surface brightness profiles are fitted with the β -model with free normalization and core radius, but we fix $\beta = 0.67$ because of low statistics. Using the β -model fit, we derive the central gas cooling time. In all objects except for 2247+0337, it is much shorter than the Hubble time; therefore, they likely contain cooling flows. The gas mass within R_x , the radius of the detectable X-ray emission, is derived using the β -model fit. The estimated temperature and $\beta = 0.67$ are substituted into equation (1) to derive the total mass. The estimated gas and total masses are listed in Table 1. For 1159+5531, the crude method yields a 30% lower gas mass and 20% lower total mass compared with the more detailed analysis in § 3.

5. DISCUSSION

5.1. Are OLEGs Really Isolated?

Central galaxies in OLEGs clearly dominate their surroundings. The brightest galaxy within the projected distance of 500 kpc around 1159+5531 is 2.9 mag fainter and may be at a different redshift. OLEGs do not show any detectable concentration of galaxies in projection down to 7.5 mag fainter than the central galaxy. However, we cannot completely exclude the existence of a dwarf galaxy population in these systems. Mulchaey & Zabludoff (1999) have studied NGC 1132, a nearby optically selected galaxy with X-ray properties similar to OLEGs and $M_R = -21.5 + 5 \log h$, and found a concentration of dwarf galaxies with M_R in the range from -15 to $-17 + 5 \log h$, consistent in number with that in X-ray-detected galaxy groups. The sensitivity of our 1159+5531 image is adequate to detect such galaxies. We do not find any evidence for the existence of a dwarf concentration around 1159+5531, but the upper limit on their number is consistent with the composite group profile presented by Mulchaey & Zabludoff. The possibility of the existence of a dwarf population around 1159+5531 and our other objects can be tested only by a detailed redshift survey.

5.2. Number Density

The volume covered by our survey contains four objects. The corresponding Bayesian lower and upper 95% confidence limits of the true number of objects are 1.97 and 9.15, respectively (see, e.g., Kraft, Burrows, & Nousek 1991). Using the dependence of the survey solid angle on limiting X-ray flux (Paper I), we find a volume of $1.32 \times 10^7 \text{ Mpc}^3$ for objects with $L_x = 2 \times 10^{43} \text{ ergs s}^{-1}$ and a slightly larger volume of $1.67 \times 10^7 \text{ Mpc}^3$ for $L_x = 4 \times 10^{43} \text{ ergs s}^{-1}$. Conservatively assuming the larger volume, we obtain the spatial density of OLEGs of $n = 2.4^{+3.1}_{-1.2} \times 10^{-7} \text{ Mpc}^{-3}$ at 90% confidence.

This number density is comparable to the number of other objects of a similar nature—compact galaxy groups and field elliptical galaxies in the corresponding X-ray and optical luminosity range. The X-ray luminosity functions from Ebeling et al. (1997) and Burns et al. (1996) show that OLEGs represent $\approx 20\%$ of all clusters and groups with $L_x > 2 \times 10^{43}$ ergs s^{-1} . The extrapolation of the X-ray luminosity functions of Hickson compact groups (HCGs) from Ponman et al. (1996) suggests that OLEGs outnumber comparably X-ray luminous HCGs by a factor of ≈ 3.5 . OLEGs are as numerous as HCGs of comparable total optical luminosity (Sulentic & Rabaça 1994). To estimate the number density of field elliptical galaxies, we used the *R*-band luminosity function derived from the Las Campanas redshift survey (Lin et al. 1996). Above a limiting absolute magnitude $M_R = -22.5 + 5 \log h$ corresponding to the luminosity of our faintest object 2114–6800 (and 2.2 mag brighter than M^*), we find the number density of *all* galaxies, $n = 2.50 \times 10^{-7}$ Mpc $^{-3}$. Most of these bright galaxies can be spectrally classified as early types (Bromley et al. 1998). Some of them should lie within rich clusters, so the above number density is an upper limit for the field population. Therefore, most, if not all, of the brightest field elliptical galaxies (with $L > 6L^*$) are OLEGs; i.e., they possess X-ray halos extending for hundreds of kiloparsecs. This also means that our OLEG sample cannot be significantly incomplete.

Markevitch (1998) derived the number density 2.9×10^{-8} Mpc $^{-3}$ for $T > 7$ keV clusters. Since the total mass scales with temperature as $T^{3/2}$, OLEGs ($T \approx 2$ keV) are 6.5 times less massive than 7 keV clusters. OLEGs outnumber such clusters by a factor of ≈ 8 , and hence their contribution to the total mass density is similar.

5.3. High Mass-to-Light Ratio

There is an indication that OLEGs have unusually high mass-to-light ratios. Within 500–1000 kpc, the radius where extended X-ray emission can still be detected, M/L in the *R*-band is in the range of 250–450 $M_\odot/L_\odot$. We find similar or slightly higher values of M/L in the *V* band. Our M/L estimates are 2–3 times higher than the *V*-band values for clusters and groups determined from the X-ray mass measurements (David et al. 1995).

Is this difference real or can it be explained by our measurement errors? The largest uncertainty in M/L is due to the inaccuracy of the total mass measurement. Our total mass estimates are essentially proportional to temperatures estimated from the L_x – T relation. A two- to threefold overestimate of T from this relation is possible, but unlikely, given the good agreement between the estimate and measurement for 1155+5531. The temperature profile of 1155+5531 allows a temperature decline by a factor of ~ 2 at 1 Mpc, which we neglect in mass calculations. The effect of such a declining temperature profile is to reduce the hydrostatic mass estimate by $\sim 40\%$ (Markevitch et al. 1998). However, Markevitch et al. observe a declining temperature profile in all hot clusters, and hence David et al. cluster masses also should be revised $\sim 40\%$ lower.

A plausible explanation of the origin of OLEGs is that they are merged compact galaxy groups (Ponman et al. 1994; Mulchaey & Zabludoff 1999). If this explanation is correct, our results imply that most of the brightest field elliptical galaxies are products of group merging and that these products are more numerous than present-day compact groups of comparable luminosity. The latter is consistent with the short estimated lifetime of compact groups (Mamon 1986). However, the high values of M/L that we find in OLEGs pose a problem for this scenario because the optical luminosity is unlikely to decrease during the galaxy merging.

Even the scarce available data indicate that OLEGs represent a new, interesting class of objects warranting a detailed X-ray and optical study. These objects are likely to have been undisturbed for a long time and thus represent the ultimate example of cluster-like systems in hydrostatic equilibrium. Forthcoming *Chandra X-Ray Observatory* observations of two objects from our sample will result in accurate profiles of the gas and total mass. If the high M/L and low gas fraction we find for 1155+5531 is confirmed, this will pose a problem for low Ω_0 estimates from the values of these quantities in clusters.

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