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BARYONICALLY CLOSED GALAXY GROUPS

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ABSTRACT

Elliptical galaxies and their groups having the largest L_x/L_B lie close to the locus $L_x = 4.3 \times 10^{43}(L_B/10^{11}\ L_{B\odot})^{1.75}$ expected for closed systems having baryon fractions equal to the cosmic mean value, $f_b \approx 0.16$. The estimated baryon fractions for several of these galaxies/groups are also close to $f_b = 0.16$ when the gas density is extrapolated to the virial radius. Evidently they are the least massive baryonically closed systems. Gas retention in these groups implies that non-gravitational heating cannot exceed about 1 keV per particle, consistent with the heating required to produce the deviation of groups from the $L_x - T$ correlation for more massive clusters. Isolated galaxies/groups with X-ray luminosities significantly lower than baryonically closed groups may have undermassive dark halos, overactive central AGNs, or higher star formation efficiencies. The virial mass and hot gas temperatures of nearly or completely closed groups correlate with the group X-ray luminosities and the optical luminosities of the group-centered elliptical galaxy, i.e. $M_{vir} \propto L_B^{1.33}$, an expected consequence of their merging history. The ratio of halo mass to the mass of the central galaxy for X-ray luminous galaxy/groups is $M_{vir}/M_* \sim 80$.

Subject headings: galaxies: elliptical and lenticular, CD – X-rays: galaxies – galaxies: clusters: general – X-rays: galaxies: clusters – galaxies: cooling flows

1. INTRODUCTION

Massive elliptical galaxies with similar optical luminosities have hot gas X-ray luminosities that range over two orders of magnitude. The origin of this scatter, shown in Figure 1, has received much attention but a full understanding remains elusive. There is evidence that gas loss by ram pressure (and tidal) stripping has reduced L_x/L_B in elliptical galaxies or groups orbiting within rich clusters of galaxies (Biller et al. 2004; Machacek et al. 2005; Sun et al. 2005). However, an enormous range in L_x/L_B also prevails among non-interacting ellipticals that are isolated or at the centers of isolated galaxy groups. The correlation between the spatial extent of the X-ray emission and L_x/L_B suggests that the driver for this scatter is a variation in the virial mass M_{vir} of the halo that surrounds otherwise similar elliptical galaxies (Mathews & Brighenti 1998). The virial mass M_{vir} and radius r_{vir} are found by fitting dark NFW halos to the total mass distribution derived from X-ray observations of the hot gas density and temperature in 10 kpc $\lesssim r < r_{vir}$, assuming hydrostatic equilibrium.

To gain further insight into the broad range of X-ray emission from optically similar galaxies, we draw attention here to those ellipticals with the largest X-ray luminosities. These isolated galaxy/groups have been variously referred to as "[X-ray] overluminous elliptical galaxies (OLEGS)" (Vikhlinin et al. 1999) or "fossil groups" (Ponman et al. 1994). The concept of fossilized groups is meant to imply that they are relics of merging among galaxies in a group environment, although all elliptical galaxies may qualify for this designation. Jones et al. (2003) provide an operational definition for fossil groups in terms of the magnitude difference between the first and second brightest group galaxies. For our purposes here we simply consider those elliptical galaxies with the largest L_x/L_B in the $L_x - L_B$ plot, many of which have been previously regarded as fossils or OLEGS. We then note that several of the best studied of these galaxies have nearly the same baryon mass fraction as the most massive galaxy clusters and the *WMAP* value, $f_b = 0.16$ (Spergel et al. 2003), i.e. they appear to be baryonically closed. Most baryons are in the hot intragroup gas.

The data in Figure 1 are mostly taken from O'Sullivan et al. (2001) (open squares), but we have added additional X-ray luminous ellipticals assembled from more recent observations (filled symbols) with properties listed in Table 1. These X-ray luminous systems define the upper envelope of the luminosity distribution in the $L_x - L_B$ plane. While all estimates of the baryon mass fraction f_b require uncertain extrapolations beyond the observations to the virial radius r_{vir}, f_b for several X-ray luminous groups in Table 1 indicate near or complete baryon closure. All data have been scaled to $H_0 = 70$ km s^{-1} Mpc^{-1}.

2. NON-GRAVITATIONAL HEATING IN THE NGC 5044 GROUP

Galaxy groups and poor clusters with $M_{vir} \lesssim 3 \times 10^{14}$ $M_\odot$ and $kT \lesssim 4$ keV are known to deviate systematically below the $L_x - T$ relation established by more massive clusters, suggesting additional non-gravitational energy by cosmic preheating or AGN activity (as reviewed by Voit 2005). Consequently, it is remarkable that groups in Table 1 with $kT \sim 1 - 2$ keV have survived with most or all of their baryonic component intact.

NGC 5044 is a good example of such a group. For the purpose of this discussion, we have made a preliminary mass model of NGC 5044 based on gas density

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and temperature profiles observed to $\sim 0.3 r_{vir} \approx 300$ kpc from Buote et al. (2003, 2004, & 2006 in prep.). In the central regions the azimuthally averaged gas density $n_{e,obs}$ was replaced with $n_{e,f} = n_{e,obs}/f^{1/2}$ where $f(r) = 1 - 0.642\exp(-r_{kpc}/20)$ (Buote et al. 2003) is the filling factor of the denser gas component at each radius responsible for most of the observed emission. The model was constructed by first setting the stellar parameters – a de Vaucouleurs profile with luminosity $L_B = 4.5 \times 10^{10}$ $L_{B\odot}$, effective radiius $R_e = 10$ kpc and stellar mass to light ratio $\Upsilon_B = 7.5$ – that establish the total stellar mass $M_{*E} = 3.4 \times 10^{11}$ $M_\odot$ and potential. The dark halo is assumed to have an NFW mass profile with an adjustable virial mass M_{vir} and concentration $c = 433 M_{vir}^{-0.125}$ expected for this mass (Bullock et al. 2001). The equation of hydrostatic equilibrium is integrated for $n_e(r)$, fixing the gas temperature $T(r)$ to fit observations and extrapolating to larger radii in a $\log T - \log r$ plot. M_{vir} and the innermost gas density are varied until an excellent fit is achieved to the $n_{e,f}(r)$ profile throughout the observed region. The resulting virial mass, $M_{vir} = 4.0 \times 10^{13}$ $M_\odot$, is similar to our previous estimate (Buote et al. 2004) and the virial radius $r_{vir} = (3M_{vir}/4\pi\Delta\rho_c)^{1/3} = 841$ kpc with $\Delta = 104$ and $\rho_c = 9.24 \times 10^{-30}$ gm cm^{-3}. When the observed gas density profile in NGC 5044 is extrapolated to r_{vir} (Buote et al. 2004; 2006 in prep.), maintaining the same power law $n_e = 0.66 r_{kpc}^{-1.45}$ cm^{-3} observed in the region $100 < r < 300$ kpc, we find that the total gas mass is $M_g = 4.8 \times 10^{12}$ $M_\odot$, in agreement with the mass model. The mass fraction in gas is $f_g \approx 0.11$. This corresponds to a baryon ratio $f_b \approx f_g/(1 - 0.12) = 0.13$, assuming a (conservative) star formation efficiency of 12% (Lin & Mohr 2004). At least 80% of the initial baryons in NGC 5044 is still bound to the group. Evidently, the non-gravitational heating received by the gas is $\lesssim 20\%$ of the gas binding energy, $E_{bind} = 9.6 \times 10^{61}$ ergs. [4] For simplicity we assume that the percentage difference between the observed f_g and the value $f_g \approx (1 - 0.12) f_b = 0.14$ expected from WMAP is proportional to the amount of non-gravitational energy that the gas received as a percentage of E_{bind}.

The gas heating efficiency associated with accretion onto the central black hole in NGC 5044 must be consistent with gas retention. The central galaxy with mass $M_* = 3.4 \times 10^{11}$ $M_\odot$ is expected to contain a black hole of mass $M_{bh} \approx 7.6 \times 10^{-5} M_*^{1.12} = 6.2 \times 10^8$ $M_\odot$ (Haering & Rix 2004). During the accretion history of the central black hole, suppose that a fraction η_h of the rest energy $M_{bh}c^2$ heats the intragroup gas, then gas retention at the 80% level suggests that $\eta_h \lesssim 0.2 E_{bind}/M_{bh}c^2 = 0.016$, although some of this energy will be radiated away. The energy radiated by NGC 5044 during several Gyrs is $E_{rad} = L_x t = 4.3 \times 10^{60} (t/5 \text{ Gyrs})$ ergs and, since no gas is observed to cool below $\sim T_{vir}/3$ in NGC 5044 (Buote et al. 2003), the minimum accretion heating efficiency is $\eta_{rad} \sim E_{rad}/M_{bh}c^2 \sim 0.004 (t/5 \text{ Gyrs})$. Evidently only a tiny fraction of the accretion energy released by the central black hole ($\sim 0.1 M_{bh}c^2$) can have heated the intragroup gas in NGC 5044. Nevertheless, substantial ongoing AGN-related heating is currently observed near the center of the NGC 5044 group (Buote et al. 2003; Mathews, Brighenti & Buote 2004).

The non-gravitational energy received by the hot intracluster gas from supernovae can be estimated from the total mass of iron observed in the NGC 5044 group,

$$M_{Fe} = 0.71 z_{Fe,gas} M_{gas} + 0.71 z_{Fe,*} \sigma M_* \qquad (1)$$

where the estimated total gas mass is $M_{gas} = 4.8 \times 10^{12}$ $M_\odot$, 0.71 is the ratio of hydrogen mass to total mass including helium, and the total stellar mass in the group is σ times larger than M_*. The mass-weighted gas iron abundance in the NGC 5044 group is $z_{Fe,gas} = 0.16 z_{Fe\odot}$ and we adopt a mean stellar abundance $z_{Fe,*} = 0.5 z_{Fe\odot}$ and $z_{Fe\odot} = 1.83 \times 10^{-3}$ (Grevesse & Sauval 1998). The total iron mass can be expressed in terms of supernova yields ($y_{II} \approx 0.1$ $M_\odot$ and $y_{Ia} \approx 0.7$ $M_\odot$) and η, the number of supernovae per $M_\odot$ of initial stars formed,

$$M_{Fe} = M_{*i}(\eta_{II} y_{II} + \eta_{Ia} y_{Ia}). \qquad (2)$$

We assume that none of the supernova iron either cooled (Brighenti & Mathews 2005) or was buoyantly expelled to $\sim r_{vir}$. If all stars formed at high redshift with a Salpeter IMF between 0.08 and 100 $M_\odot$ the number of stars with mass above $8 M_\odot$ that become Type II supernovae is $\eta_{II} = 0.0068$ per $M_\odot$. If σM_* is the current stellar mass in the group, the initial mass is $M_{*i} \approx \sigma M_*/(1 - \beta)$ where $\beta \approx 0.3$ is the fraction of the original stellar mass ejected from stars (Brighenti & Mathews 1999). If the iron mass M_{Fe} is eliminated between the two equations above, we find that the number of Type Ia supernova per $M_\odot$ of initial stars is $\eta_{Ia} \approx 6.7 \times 10^{-4} \sigma^{-1}$. The total energy released by both types of supernovae is

$$E_{sn} = M_{*i}(\eta_{II} + \eta_{Ia}) 10^{51} \approx 1.1 \times 10^{61} \quad \text{ergs} \qquad (3)$$

where we assume 10^{51} ergs per supernova and $\sigma = 3$. Since $E_{sn}/E_{bind} \approx 0.11$ it is possible that supernovae energy could eject $\sim 10\%$ of the baryons from the group. But our assumption that all of the SNII energy is communicated to the hot gas may not be plausible since it makes no allowance for radiation losses in SNII remnants. Of course a flatter IMF (e.g. Brighenti & Mathews 1999; Nagashima et al. 2005) could generate enough SNII energy to eject 20% of the gas (e.g. Brighenti & Mathews 2001). Clearly, the large baryon fraction f_b observed in NGC 5044 and other X-ray luminous groups imposes a significant constraint on non-gravitational heating.

3. L_B AND THE VIRIAL MASS

The X-ray luminosity of the groups with filled symbols in Figure 1 along the upper envelope of the L_x–L_B distribution correlates with L_B as $L_x \approx 1.7 \times 10^{21} (L_B/L_{B\odot})^2$ erg s^{-1} (also see Jones et al. 2003). If these groups are essentially baryonically closed, as we propose here, then L_B for the group-centered E galaxy should also increase with the virial mass. This correlation is shown in Figure 2a where we plot those groups from Table 1 having known estimated M_{vir}. Similar $L_B - M_{vir}$ correlations have been found from the 2MASS survey (Lin & Mohr 2004) and the galaxy-galaxy lensing data of Cooray & Milosavljevic (2005) who find $M_{vir} \propto L_B^{1.33}$, which agrees

[4] The binding energy is found by computing the double integral $E_{bind} = \int_0^{r_{vir}} \rho_g 4\pi r^2 dr \int_r^\infty g(r')dr'$ where ρ_g and $g(r) = GM(r)/r^2$ are the gas density and gravitational acceleration from our mass model for NGC 5044.

well with the group data in Figure 2a [5]. The $L_B - M_{vir}$ correlation arises because group-centered elliptical galaxies grow by mergers as massive satellite group galaxies undergo dynamical friction in the dark halos. Progressively more massive halos contain more mergeable galaxies so the final L_B of the group-centered elliptical increases with M_{vir} until $M_{vir} \gtrsim 10^{14}\ M_\odot$ where dynamical friction is reduced by the small galaxy/halo mass ratio. All baryonically closed groups have been dynamically processed in this way.

The ratio of the total halo mass to that of the central galaxy M_{vir}/M_* is of particular interest. The correlation $M_{vir} = 1.12 \times 10^{14}(L_B/10^{11}L_{B\odot})^{1.33}\ M_\odot$ shown in Figure 2a (dashed line), when combined with the stellar mass to light ratio $M_*/L_B = 7.1(L_B/10^{10})^{0.29}$ (Trujillo et al. 2004), results in $M_{vir}/M_* \approx 80(M_*/10^{12}M_\odot)^{0.03}$. This ratio is larger than the dynamical masses determined from the Sloan Digital Sky Survey: $M_{vir}/M_* \sim 15 - 20$ (based on M_{vir}/L_B from Prada et al. 2003) and $M_{vir}/M_* \sim 7 - 30$ (Padmanabhan et al. 2004) for E galaxies comparable to those in Table 1. This suggests that optically similar elliptical galaxies with larger L_x may have somewhat more massive dark halos. The mean gas temperature for these groups plotted in Figure 2b also correlates with optical luminosity of the group-centered galaxy as indicated by the dotted line with slope $T \propto L_B^{0.60}$. Since $L_x \propto L_B^2$ from the Table 1 data in Figure 1, both M_{vir} and T also correlate with L_x, $M_{vir} \propto L_x^{0.7}$ and $L_x \propto T^{3.3}$.

The X-ray luminosity of baryonically closed groups ($M_{gas} \propto M_{vir}$) scales approximately as $L_x \propto \langle n_e \rangle M_{gas} \propto M_{vir}^2/r_{vir}^3 \propto M_{vir}$ [For the mean gas temperatures of the groups in Table 1, $1 \lesssim kT \lesssim 3$ keV, the bolometric X-ray emissivity is insensitive to temperature (Sutherland & Dopita 1993)] . However, the $L_x - M_{vir}$ relation also depends on the NFW concentration $c = 450(M_{vir}/M_\odot)^{-0.128}$ (Bullock et al. 2001). We estimate $L_x(c, M_{vir})$ for closed groups ($f_g = f_b - f_* \approx 0.14$) by filling NFW potentials with isothermal gas with $T = 2.22 \times 10^7(M_{vir}/10^{14}M_\odot)^{0.54}$ K taken from Shimizu et al. (2003). The bolometric X-ray luminosity within r_{vir} is $L_x = 4.9 \times 10^{43}(M_{vir}/10^{14}M_\odot)^{1.3}$ erg s^{-1} for $10^{13.5} \lesssim M_{vir} \lesssim 10^{14.5}M_\odot$, where we assume $M_{vir} \propto L_B^{1.33}$ from Figure 2a (dashed line). This locus of maximum X-ray luminosity, $L_x = 4.3 \times 10^{43}(L_B/10^{11}\ L_{B\odot})^{1.75}$ erg s^{-1}, is shown with a dotted line in Figure 1. If the gas temperature $T \propto T_{vir} \propto M_{vir}^{2/3}$ then $L_x \propto M_{vir}^{1.3}$ suggests that $L_x \propto T^2$ similar to Kaiser (1986).

4. CONCLUSIONS

We propose that galaxy groups lying near the upper envelope of the $L_x - L_B$ distribution in Figure 1 are nearly or completely baryonically closed boxes similar to more massive clusters. This conclusion is supported by the baryon fraction estimates listed in Table 1 and the proximity of the observations in Figure 1 to the approximate dotted line locus for the maximum L_x expected from baryonically closed groups observed to r_{vir}. The projected X-ray luminosity of our mass model for NGC 5044 beyond $\sim 0.1r_{vir}$ varies as $L_x(r_{proj}) \propto r_{proj}^{0.28}$ so we expect that L_x for galaxies with filled symbol points in Figure 1 will creep upward toward the dotted line when observed with larger apertures and more sensitive detectors. Nevertheless, we do not expect to find galaxy/groups in the future that lie significantly above the filled circles and squares in Figure 1.

Baryonically closed groups provide interesting constraints on the amount of non-gravitational heating acquired by the intragroup gas. To retain most or all of the gas in these groups, the gas heating by the central black hole (AGN) must be $\eta_h M_{bh}c^2 \lesssim 0.016M_{bh}c^2$ or $\lesssim 1$ keV per particle, consistent with typical values $\sim 0.7-1$ keV per particle required to account for deviations from self-similarity in the $L_x - T$ plot for clusters (e.g. Tornatore et al. 2003; Voit 2005). We also find that the combined energy of all past supernovae is insufficient to remove significant amounts of intragroup gas unless the IMF is flatter than Salpeter (Brighenti & Mathews 1999, 2001).

Another necessary attribute of baryonically closed groups is that they are spatially isolated, i.e. they have not lost mass by ram-stripping during mergers with comparable or larger systems. Spatially isolated E galaxies and groups are of particular interest because of the strong limits they impose on non-gravitational heating. It is therefore remarkable that some isolated E galaxies have much lower L_x than ellipticals in baryonically closed groups. For example, in Figure 1 we mark with + symbols two isolated E galaxies found recently by Reda et al. (2004) that are near the bottom of the distribution. This large variation of L_x for isolated Es of similar L_B in Figure 1 may result from normal cosmic variance. It would be interesting to determine if these and other isolated galaxies have unusually undermassive dark halos (allowing winds), if they contain more energetically active (and massive) black holes or if their star formation efficiencies are unusually large, since such variations could help explain why these isolated galaxy/groups are not baryonically closed. By this means it will eventually be possible to determine if the non-gravitational heating arises primarily from the central black hole. It would also be worthwhile to assemble M_{vir}, $\langle T \rangle$ and optical luminosities for all isolated E galaxies and groups throughout the $L_x - L_B$ plane.

Finally, we have shown that baryonically closed groups can inform us about the important relationship between the optical luminosity and mass of the group-centered galaxy and the mass of the surrounding (group) dark halo. The preliminary data currently available suggest that the dark halos are about ~ 80 times more massive than the central (non-cD) elliptical galaxy. These conclusions can be explored further in the $L_x - L_B$ plane by considering all elliptical galaxies for which X-ray observations provide accurate M_{vir}.

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[5] M_{vir} for NGC 6482 (the leftmost point in Figure 2a) may be significantly underestimated since the X-ray observations extend only to $\sim$ 30 kpc, close to the expected transition between the influence of the dark halo mass and the much smaller stellar mass.

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TABLE 1
LUMINOUS GALAXY GROUPS[a]

galaxy group	$\log(L_B/L_{B\odot})$	$\log L_{x,bol}$ (erg s^{-1})	kT (keV)	$\log M_{vir}$ ($M_\odot$)	f_b	Ref.[b]
NGC5044	10.76	42.80	1.2	13.60	~ 0.13	1
RXJ1159	11.09	43.05	2.2	14.15	~ 0.04	2
WJ943.7	10.94	43.07	1.7	13.74	~ 0.15[c]	3
RXJ0419	10.64	42.75	1.4	$\sim$13.6	~ 0.03[c]	4
NGC6482	10.47	42.04	0.7	12.60	~ 0.18[c]	5
ESO3060170	11.30	43.82	2.7	14.25	NA	6
RXJ1340	11.02	43.11	2.3	14.33[d]	NA	2,10
RXJ2114	10.96	43.01	2.1	14.27[d]	NA	2
RXJ2247	11.13	43.32	2.8	14.45[d]	NA	2
NGC1132	10.73	42.71	1.0	13.52	NA	7,8
RXJ1416	11.24	44.05	1.5	NA	NA	9
RXJ1119	10.36	41.94	NA	NA	NA	9
RXJ1256	11.16	43.49	NA	NA	NA	9
RXJ1331	10.68	42.48	NA	NA	NA	9
RXJ1552	11.12	43.51	NA	NA	NA	9
RXJ0116	10.76	42.94	NA	NA	NA	9

[a]All data scaled to $H_0 = 70$ km s^{-1} Mpc^{-1}

[b]References: 1 Buote et al. (2004); 2 Vikhlinin, A. et al. (1999); 3 Rasmussen, J. & Ponman, T. J. (2004); 4 Kawaharada, M. et al. (2003); 5 Khosroshahi, H. G., Jones, L. R. & Ponman, (2004); 6 Sun, M. et al. (2004); 7 Mulchaey, J. S. & Zabludoff (1999); 8 Gastaldello, F. et al. (2005); 9 Jones, L. R. et al. (2003); 10 Jones, L. R. et al. (2001)

[c]Estimated from gas mass ratio by scaling up by 1.11

[d]Reference 2 provided values of the total mass $M(r_x)$ within radius r_x. We used the definition of $r_{vir}(M_{vir})$ with $c(M_{vir})$ and $y_x = cr_x/r_{vir}$ to determine $M_{vir} = M(r_x)f(c)/f(y_x)$ from the NFW mass profile where $f(x) = \ln(1+x) - x/(1+x)$.

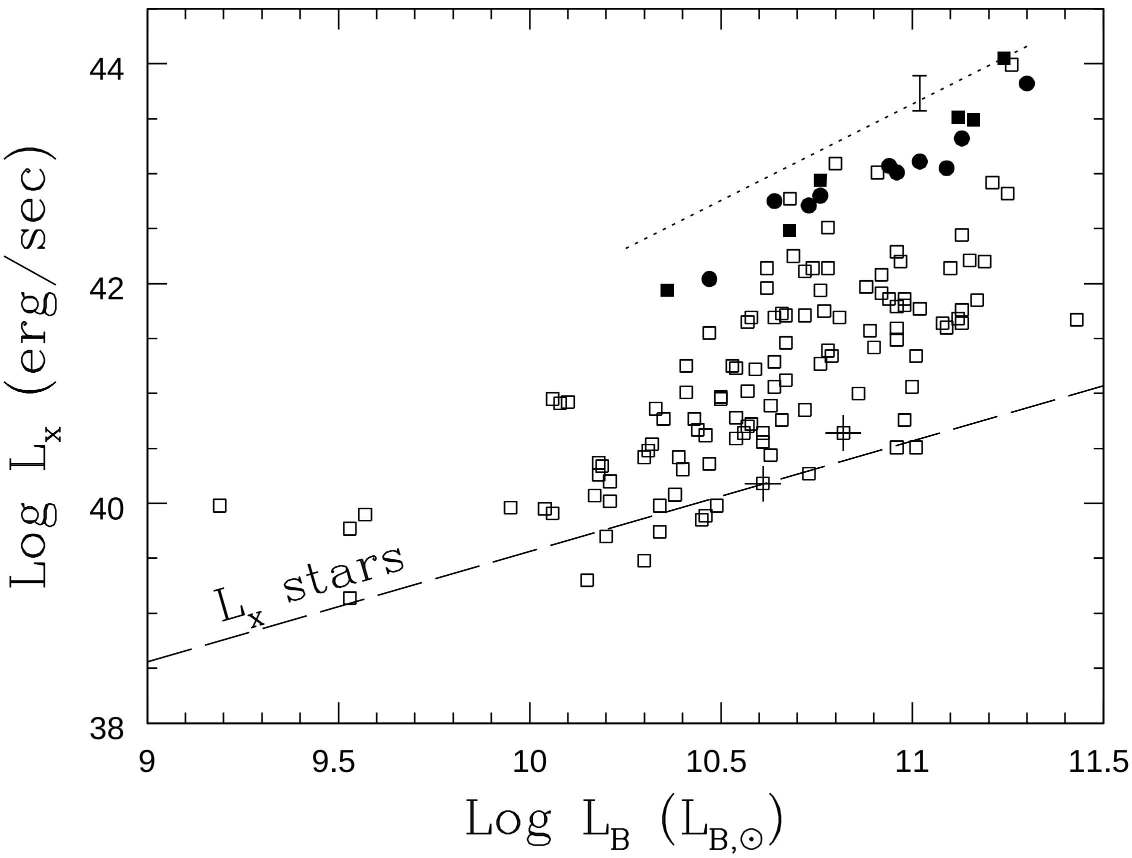

FIG. 1.— Plot of the bolometric X-ray luminosity and B-band optical luminosity for elliptical galaxies (RC3 type $T \leq -4$) from O'Sullivan et al. (2001) (open squares). Only X-ray detected galaxies are shown. The filled circles (squares) are X-ray luminous ellipticals with estimated (unknown) virial masses as listed in Table 1. Two isolated elliptical galaxies (NGC 3557 and NGC 4697) are marked with + symbols. The dashed line approximately represents the stellar X-ray emission from binary stars (Kim & Fabbiano 2004). The dotted line $L_x = 4.3 \times 10^{43}(L_B/10^{11}\ L_{B\odot})^{1.75}$ is the locus of maximum L_x for NFW halos maximally filled with gaseous baryons ($f_g = 0.14$); the error bars show the effect of a 1σ change in concentration $c(M_{vir})$ expected from cosmic variation (Bullock et al. 2001). On average the filled symbols lie ~ 0.33 below the dotted line; since $L_x \propto f_g^2$ and the observed $L_x < L_x(r_{vir})$, they have gas filling factors $f_g \gtrsim 0.08$.

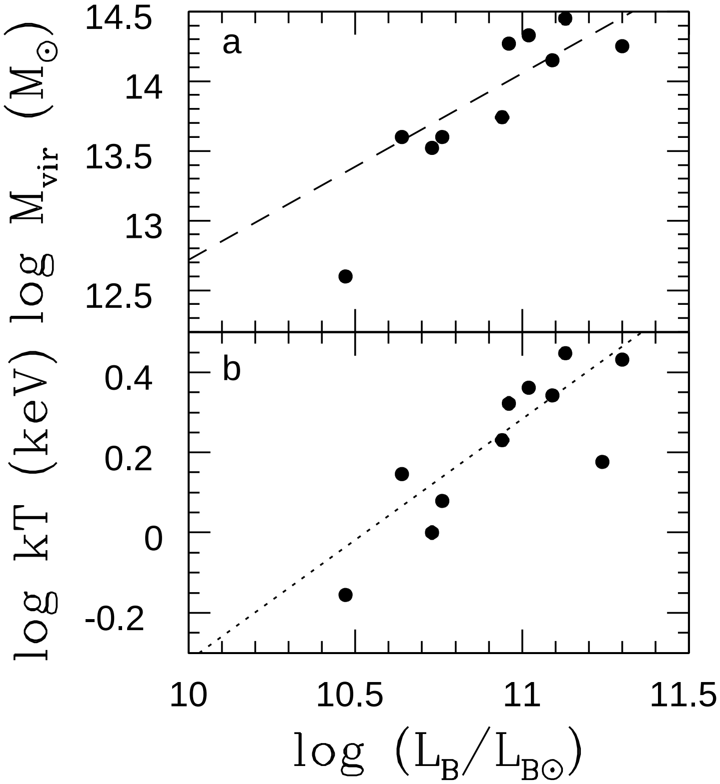

FIG. 2.— Plots of optical luminosity of baryonically closed groups against virial mass and mean gas temperature. (a) The dashed line in the upper panel shows the variation $M_{vir} \propto L_B^{1.33}$ based on weak lensing. (b) The dotted line shows the correlation $T \propto L_B^{0.60}$.