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SMALL IS BEAUTIFUL – RESULTS FROM GALAXY GROUPS

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Galaxy groups have potentials deep enough to bring galaxies into strong interaction, and to retain much of any material detached or ejected from them. However, unlike rich clusters, groups have virial temperatures similar to those of individual galaxies, so that energetic events within galaxies can have a significant impact on the properties of the system as a whole. Groups therefore provide a powerful probe of galaxy evolution. Here we concentrate on the effects of the group environment on the X-ray properties of galaxies. We find that late-type galaxies in groups have X-ray properties very similar to those in the field, but that early-type galaxies can have strikingly higher X-ray luminosities if they are located in the centre of a group potential. Failure to recognise this last effect has introduced a good deal of confusion into past work on the X-ray properties of early-type galaxies.

1 Introduction

Approximately half of galaxies are found in galaxy groups [1], and group galaxies may show some differences from their counterparts in the field. For example, there is evidence that some spirals interact with their environment [2], and with each other [3,4], whilst early-type galaxies in groups are less likely to have boxy isophotes and more likely to have irregular isophotes than comparable ellipticals in other environments [5]. Many of these features can be attributed to the effects of the group environment in which the galaxy is found.

What of the X-ray properties of galaxies? There are two main sources for the X-ray emission from normal galaxies: stellar sources and hot diffuse interstellar gas. Emission from bright early-type galaxies is dominated by the hot diffuse component [6,7] whilst in late-type and less luminous early-types, the emission is primarily from stellar sources [8,9]. Previous studies of the X-ray properties of both spiral [10] and elliptical [11,12,13,14] galaxies, have found that while the X-ray luminosity of late-type galaxies scales roughly with the optical luminosity, the same relation for early-type galaxies is considerably steeper and shows much more scatter.

However, the above work has mostly taken little account of the possible effects of the group environment on the X-ray properties of galaxies. Our aim here is to compare the properties of group and field galaxies, to look for the ways in which environmental effects may contribute to the range in properties which is seen. In practice, some care is required in such a study, to avoid serious contamination of galaxy X-ray fluxes by emission from the intergalactic medium surrounding them. Further details of this study can be found in Helsdon et al [15].

2 Galaxy sample and data analysis

For the present study we have combined the sample of mostly loose groups studied by Helsdon & Ponman [16] with additional data for compact galaxy groups. We use only galaxies from groups in which a hot intergalactic medium is detected, since this confirms that these groups are genuine mass concentrations, as opposed to chance line-of-sight superpositions.

Helsdon & Ponman [16] compiled a sample of 24 X-ray bright groups observed with the ROSAT PSPC. In the case of compact galaxy groups, the tight configuration of the major group galaxies (typically separated by only a few arcminutes) can lead to serious problems of confusion, and contamination of galaxy fluxes by diffuse group emission. We have therefore added to the sample all the Hickson Compact Group [17] (HCG) galaxies observed by the ROSAT HRI. This resulted in a final sample of 33 groups: 11 HCGs with HRI data and 22 other groups with PSPC data.

In the case of the PSPC data, 2-dimensional models of the group emission were available for each of the groups [16]. For a number of systems, these model fits indicated the presence of a central cusp, in addition to more extended emission associated with the group as a whole. Such central components invariably coincide with a central galaxy, which we refer to hereafter as a 'central-dominant group galaxy'. Such a galaxy is usually, but not always, the optically brightest group member. In such a case, we take the central X-ray component to be the emission associated with the galaxy. For these and all the other galaxies we are able to use the group models to remove the group contribution to the galaxy flux.

The higher resolution of the HRI generally provides a clear separation between the galaxy and group emission. Radial profiles centred on each galaxy were used to determine the radial extent of galaxy-related emission, and the galaxy count rate was then extracted from a circle encompassing this emission. In most cases the background in the HRI was flat, and was determined from a large source-free region near the centre of the field. In a few cases where group emission was especially bright, we used model fits to remove group emission in a fashion similar to the PSPC data.

Source count rates, together with Poisson errors, were extracted, background subtracted, and converted to unabsorbed bolometric luminosities assuming a 1 keV Raymond & Smith [18] model with 0.25 solar metallicity. 3 sigma limits were calculated for non-detected galaxies. B-band luminosities were derived using magnitudes from NED, and assuming a solar blue luminosity of 5.41×10^{32} erg s^{-1}.

3 Late-type galaxies

Figure 1 shows the L_X:L_B relation for the late-type galaxies in our sample. No significant difference in the relation is apparent between the subsamples in compact and loose groups, so we have combined the two. It is clear that two points stand out from the trend described by the rest. The upper of these is HCG91a, a Seyfert 1 with powerful central point-like X-ray source associated with the central AGN. The second high point is HCG48b which is not a known AGN, but seems very likely to contain an active nucleus on the basis of the properties reported here. Since we wish to explore the X-ray properties of *normal* galaxies, we exclude these galaxies from the statistical analysis below.

The best fit line (solid) shown in Figure 1, derived using survival analysis techniques, which include the upper limits in the data, is

$$\log L_X = (1.07 \pm 0.3) \log L_B + (29.2 \pm 2.1).$$

For comparison we also plot the regression line of Shapley et al [19] who derived the L_X:L_B relation for a large sample of spirals (covering a range of environments). This relationship

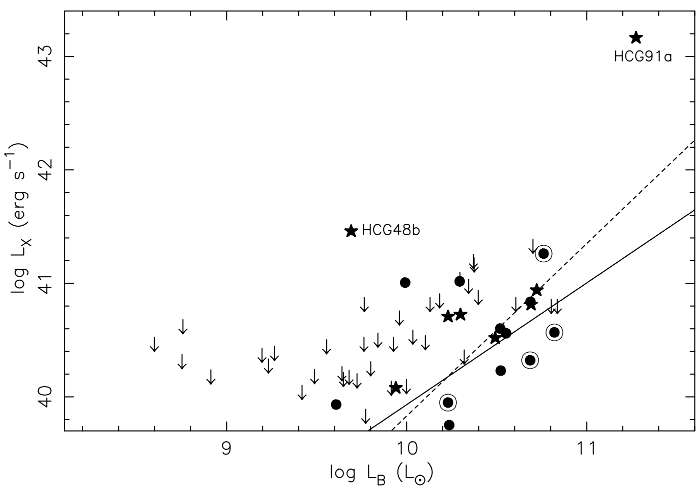

Figure 1: L_X:L_B relation for the late-type group galaxies. Arrows represent upper limits, other points are detections, with stars representing likely starbursts (or AGN), ringed circles non-starbursts and solid circles late-types whose activity is unknown. The solid line is the best fit to all the data, and the dashed line shows the relation [19] for a large sample of late-type galaxies observed by *Einstein*.

(slope=1.52±0.1, intercept=24.6), whilst steeper, lies within 2σ of the slope derived here. It is therefore not clear that our results are in conflict with those of Shapley et al, especially since these authors find evidence for extra emission (possibly from a hot halo) in the largest spirals, which are mostly absent from our sample.

In galaxy groups it might be expected that galaxy interactions may result in starbursts which could increase the X-ray to optical luminosity ratio [20]. We identify starbursts on the basis of their FIR colours ($f_{60}/f_{100} > 0.4$, though AGN may also have such warm FIR colours. Of the 12 galaxies for which FIR colour is available, the starbursts (or AGN) lie above the best fit line (8 galaxies including HCG91a and HCG48b), whilst non-starbursts generally lie below it (3 out of 4 galaxies). However, this difference is not large, and our results suggest that whilst some late-type galaxies in groups may have a small enhancement of their X-ray emission (relative to the optical), in general these galaxies follow the same L_X:L_B relation (and also L_X:L_{FIR} relation, not shown here) as galaxies in other environments.

4 Early-type galaxies

Figure 2 shows the L_X:L_B relation for the early-type galaxies in our sample. Again, no significant difference is apparent between the compact and loose group samples. The crossed circles represent the non-central group galaxy detections and the arrows upper limits. Shaded squares are central-dominant group galaxies. Also plotted for comparison are the best fit to the early-type galaxy L_X:L_B relation as determined by Beuing et al [14], on the basis of their study of a large sample of early-type galaxies derived from the ROSAT All Sky Survey (RASS), and an estimate of the discrete source contribution. This latter estimate was derived using the mean hard spectral component derived from ASCA observations [21], and converted to our energy band. It can be seen to constitute a reasonable lower envelope for the X-ray luminosity of the galaxies in our sample. There is recent evidence to suggest that there is also a very soft component asociated with discrete sources [22,23]. If this component is present in all galaxies its effect on our estimated discrete source contribution would be to increase it by a factor of $\sim$2.

Using survival analysis to fit a linear trend to the data, including the upper limits available, we obtain

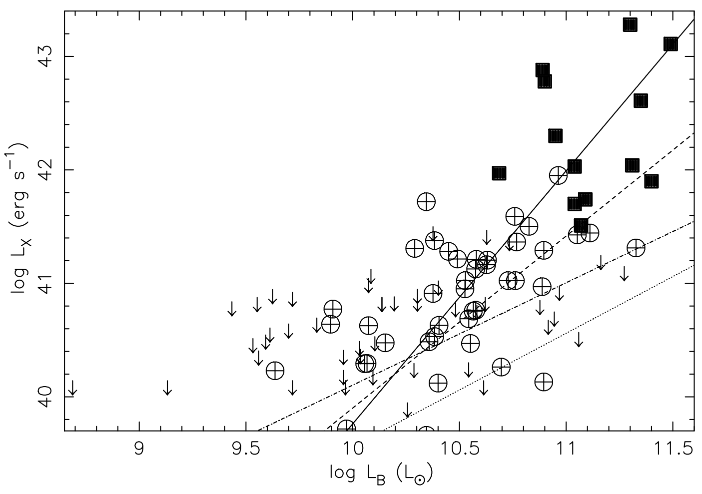

Figure 2: L_X:L_B relation for the early-type group galaxies. The shaded squares represent the central-dominant group ellipticals, circles with crosses other detected early-type galaxies in groups, and arrows upper limits. Also plotted on the graph are the following lines, the L_X:L_B relation as derived by Beuing et al. [14] (solid line), an estimate of the discrete source contribution (dotted line), the best fit to the full group galaxy sample (dashed line) and the best fit to the group sample excluding central dominant galaxies (dot-dash line).

$$\log L_X = (1.5 \pm 0.2) \log L_B + (24.7 \pm 2.0),$$

which is plotted as the dashed line in Figure 2. Although this fit is flatter than the Beuing [14] line (slope=2.23 $\pm$ 0.12), a significant fraction of our data lie in the region $\log L_X \leq 40.5$, where previous work indicates that the slope of the relation is approximately unity [12]. We therefore expect a somewhat flatter slope than derived by Beuing et al, who had many more luminous galaxies in their sample. In fact if we restrict the fit to the more luminous galaxies the slope does indeed steepen to ~ 2.2.

However it is clear that the central-dominant group galaxies all lie in the upper right region of the graph. This along with their central position in the group suggests that they may not be typical of other early-type group galaxies. Thus we also fit a regression line to the data after excluding all central-dominant galaxies, obtaining a best fit

$$\log L_X = (0.90 \pm 0.18) \log L_B + (31.1 \pm 1.8),$$

which is significantly flatter than the previous fit and is plotted as the dot-dash line in Figure 2. Since this line has a slope consistent with unity, one interpretation might be that the X-ray emission is primarily from stellar sources, and that these non-central group galaxies do not contain a significant hot halo. However the level of this line is a factor ~ 2.5 above the expected hard discrete source contribution. Even if a soft component is included in the discrete source contribution, many of these galaxies will still lie above the line, suggesting that they do have hot gas halos.

In Fig. 3 we show the X-ray to optical luminosity ratios of the central-dominant (ellipses) and other (crosses) early-type group galaxies, grouped into bins in L_B. Also shown for comparison is the same ratio for a small sample of *isolated* early-type galaxies [15]. The L_X/L_B ratio for both non-central group galaxies and isolated galaxies is consistent with a constant $\log L_X/L_B$ value of ≈ 30 (erg s$^{-1} L_\odot^{-1}$), whilst the central dominant group galaxies are typically at least an order of magnitude more X-ray luminous than other galaxies of similar optical luminosity.

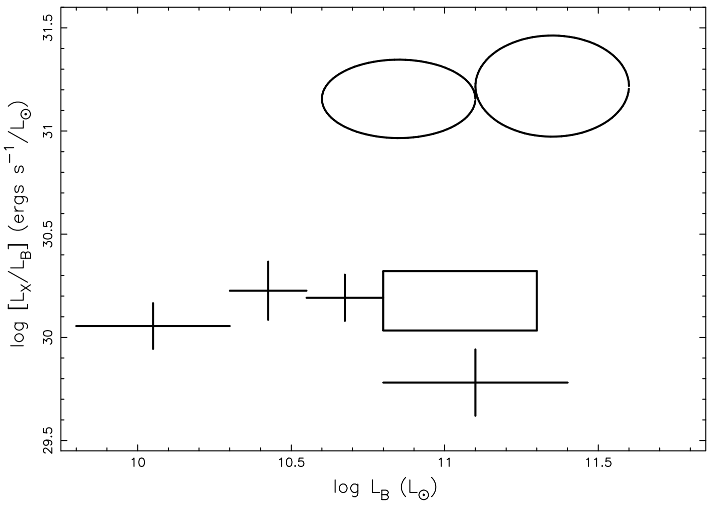

Figure 3: L_X/L_B versus L_B for the binned data for group and isolated early-type galaxies derived in this paper. Ellipses represent central-dominant group galaxies, crosses non-central group galaxies and the box isolated galaxies.

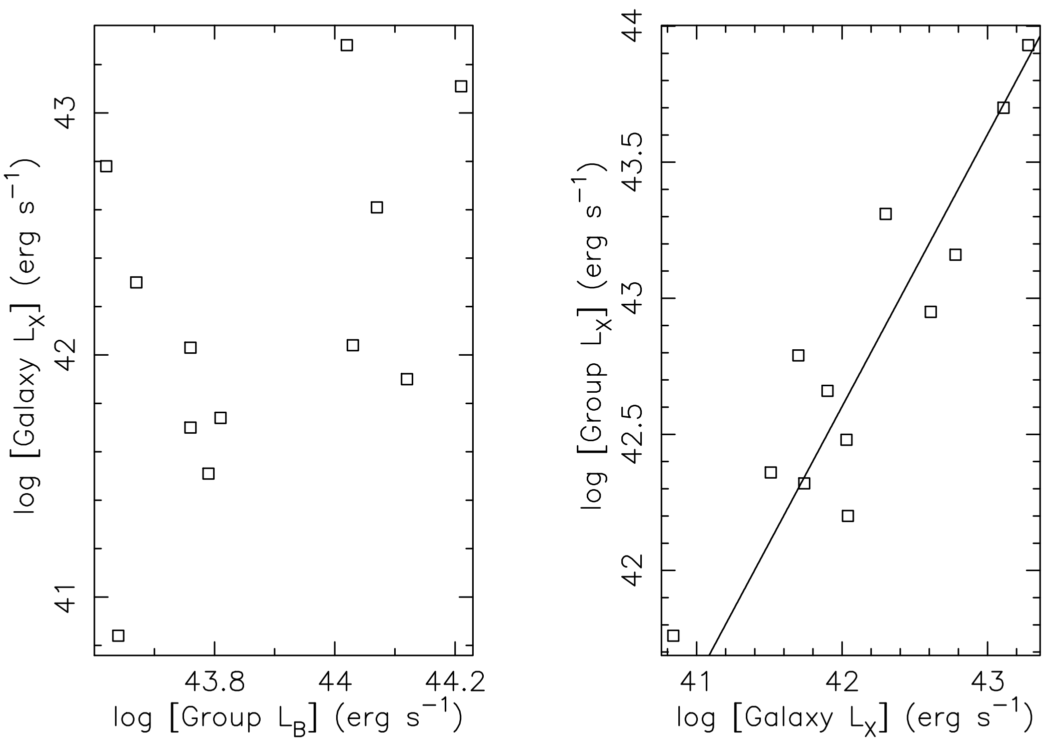

Figure 4: X-ray luminosity for group-dominant early-type galaxies is plotted against (left) the blue luminosity of the galaxy, and (right) the total L_X of the group. The correlation with group properties is much stronger, and a trend L_{gal}=$0.25L_{grp}$ (solid line) provides a reasonable fit.

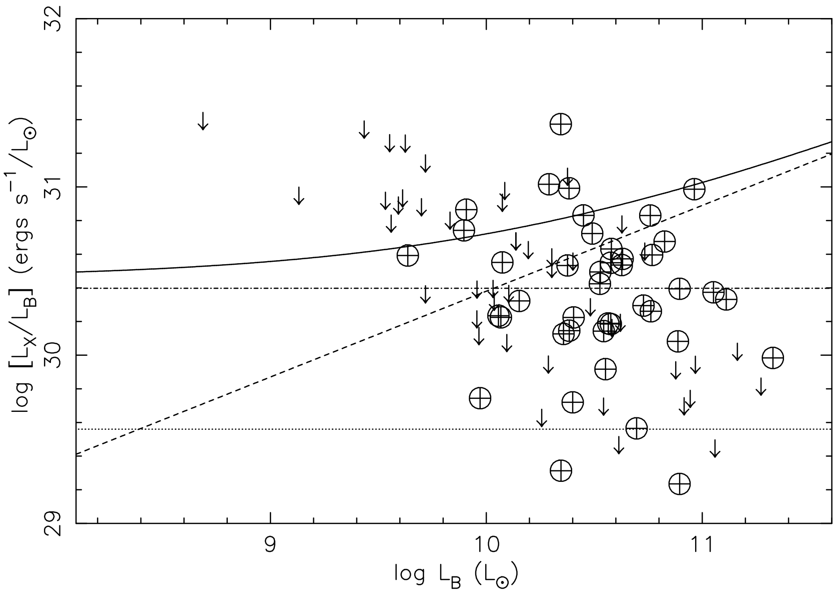

Figure 5: log L_X/L_B vs log L_B for the non-central galaxies. The dotted line is estimate of discrete source contribution, dot-dash line an estimate of energy available from SN1a, dashed line an estimate of gravitational energy, and solid line the sum of all these terms.

To explore this, in Fig.4 we plot the X-ray luminosities of central-dominant galaxies against their optical luminosities, and against the L_X of the group in which they are the central member. It is clear that their X-ray properties are much more strongly related to the *group* properties. It seems very likely that these central X-ray components are actually a group cooling flow, focussed onto the central group galaxy, rather than a normal galaxy halo. As such, they should not be combined with other early-type galaxies in a joint analysis, as has been common practice in the past. In fact, since these bright galaxies are prominent and easily studied, they have attracted a good deal of attention, and consitute a substantial fraction of many X-ray samples.

Once central-dominant galaxies are excluded, our results indicate that early-type galaxies outside clusters have an apparently universal mean value of L_X/L_B, which shows little sign of variation with optical luminosity, and appears very similar to the value for isolated galaxies. Earlier results to the contrary appear to result from the effects of including central-dominant galaxies, and also in some cases from contamination of L_X values by intergalactic emission. Once central-dominant galaxies are excluded, the scatter in L_X/L_B is reduced, but as can be seen in Figure 5, it is still substantial, varying over a factor of 20-30 for galaxies of a given optical luminosity.

It is instructive to compare the observed L_X/L_B values with the three lines marked on Figure 5. The horizontal dotted line marks the expected discrete source contribution. Whilst this line lies close to the lower bound of the data, we note that a number of galaxies do fall somewhat below it, especially if the line is raised to accomodate the soft component to the discrete source spectrum reported by Irwin and Sarazin [22,23]. These authors also note that their derived discrete source contribution shows apparently real variations, by a factor of at least three, from one galaxy to another. Attributing this component primarily to low mass X-ray binaries, they argue that such variations may reflect the abundance of neutron star remnants in a galaxy, which in turn is sensitive to the initial mass function of its stars. Note that, unlike Irwin & Sarazin, we do not observe that only *small* galaxies have exceptionally low values of L_X/L_B.

The upper horizontal line in Figure 5 corresponds to the energy available from type Ia supernovae. This lies within the distribution of points, a factor ~ 2.5 above the characteristic mean value of 10^{30}erg s^{-1}L$_{\odot}^{-1}$ (Fig.6). What is the source of the additional luminosity in those galaxies which lie above the SNIa line? There should be a contribution from the velocity dispersion of mass-losing stars (the stellar ejecta have an initial bulk kinetic energy which will be thermalised in the surrounding interstellar medium) and another from the gravitational work done as the gas cools and flows towards the centre of the galaxy [11,13]. Both these contributions scale as the square of the velocity dispersion. Using the Faber-Jackson relation [24], and following the analysis of Canizares et al [11], adopting a King profile galaxy and assuming that that the gas flows into the centre before cooling out ($f = A = 1$ in their terminology), we obtain the 'gravitational' line, $\log L_{grav} = 25.28 + 1.51 \log L_B$, marked in Figure 5, which is uncertain by a factor of a few, depending on the radius at which gas drops out of the cooling flow, and the mass of the dark galaxy halo.

Adding the discrete source, SNIa and gravitational terms gives an upper envelope for L_X/L_B, which is shown in Figure 5. Three of the four galaxies which lie significantly above this line in the plot are known to be peculiar. The highest, HCG15d, is an interacting galaxy which also a radio source. The HRI emission from this galaxy is dominated by a central point-like source which is most likely an AGN. The two galaxies above the line with $\log(L_X/L_B) \approx 31$ and log $L_B \approx 10.3$ are a Seyfert 2 and a starbursting S0 galaxy.

Our conclusion, then, is that all non-central-dominant early-type galaxies within our sample, apart from a handful which are mostly peculiar, populate a band in L_X/L_B which lies between the discrete source contribution and the expected luminosity from discrete sources plus a cooling halo of gas released from galactic stars. This band covers a range of L_X/L_B which changes only weakly with L_B (the lower bound in Figure 5 is horizontal, whilst the upper bound rises by only a factor ~ 3 over the range $L_B = 10^9 - 10^{11}L_{\odot}$), and where we have reasonable data ($L_B = 10^{10} - 10^{11}L_{\odot}$), our galaxies appear to populate the whole band. It is therefore not surprising that the mean L_X/L_B ratio shows no significant trend with L_B. Larger samples of galaxies would be required to convincingly resolve any trend associated with the upper boundary of the band.

The fact that group galaxies (at least in the range $L_B = 10^{10} - 11^{10}L_{\odot}$, where we have good coverage) span the full range from discrete source to full cooling halo lines, indicates that their hot halos cover a wide range of states. The most X-ray underluminous systems have either lost all their gas as a result of some recent stripping or star formation event, or are in a wind phase, in which most of the gas lost by stars streams out of the galaxy in a fast, low-density wind [25]. Galaxies with intermediate L_X/L_B values may be in 'partial wind' stages [26], and high resolution X-ray studies with Chandra and XMM-Newton can be used to search for central cooling flows within such systems. The non-central galaxies with the highest values of L_X/L_B are likely to have hot hydrostatic halos with fully developed galactic cooling flows. However unlike central dominant galaxies, we see no evidence that these non-central galaxies have excess X-ray luminosity due to accretion of external gas from the group. Presumably their motion within the group prevents this.

Turning finally to the the central-dominant group galaxies – these mostly fall above the upper boundary marked in Figure 5. Gas loss from within the galaxy is unable to explain the high luminosity and temperature, and the large extent of the X-ray emission in these galaxies [27,28]. It appears that additional infalling material is required to adequately reproduce their observed properties [29,27]. The most likely origin of this infalling material, for dominant group galaxies, is a group cooling flow, since, as we have seen, the X-ray properties of these galaxies appear to be more closely related to the group than to the galaxy itself [30].

If this picture is correct, the most X-ray over-luminous early-type galaxies should be found in the centres of undisturbed bright groups and clusters. Other early-type galaxies within galaxy systems should have much lower values of L_X/L_B, unless of course they have been the central galaxy of a group which has recently merged with the present cluster. In addition, disturbed clusters which show no evidence of any cooling flow would be expected to contain central galaxies that are less X-ray overluminous than clusters and groups with cooling flows.

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