A ROSAT survey of Hickson’s compact galaxy groups

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ABSTRACT

We report the results of an almost complete survey of the X-ray properties of Hickson’s compact
galaxy groups with the ROSAT PSPC. Diffuse X-ray emission is detected from 22 groups.
We infer that hot intragroup gas is present in \( \gtrsim 75\% \) of these systems and derive their X-
ray luminosity function. Earlier reports that only spiral-poor systems exhibit diffuse X-ray
emission are found to be incorrect. Strong correlations are found between the X-ray luminosity
and both the gas temperature and the velocity dispersion of the group galaxies. We argue
that these properties provide strong evidence that most of these groups are genuinely compact
configurations, rather than line-of-sight superpositions. Comparison with the X-ray properties
of galaxy clusters indicate a significant steepening of the \( L : T \) relation below \( T \sim 1 \) keV, which
may result from the action of galaxy winds.

1 INTRODUCTION

Approximately half of all galaxies are found within groups which are probably bound (Tully
1987). Whilst groups are very numerous, they are hard to identify with confidence as gravita-
tionally bound systems, even in redshift catalogues, due to the problems of contamination and
small number statistics which attend such poor systems. Compact galaxy groups are ones in
which the galaxies are separated on the sky by only a few galactic radii. Only a small fraction
of groups fall into this category, but due to their sometimes spectacular appearance, and to
the comparative ease with which they can be discriminated from the field, these systems have
received a good deal of attention.

The most widely studied collection of compact groups are the Hickson compact groups (HCGs)
compiled by Hickson (1982) by applying a set of well defined criteria for population, surface
density and isolation to the Palomar Sky Survey (E band) plate collection. Numerous follow-
up studies of Hickson’s catalogue of 100 groups have shown that many galaxies in HCGs show
morphological or kinematical peculiarities (Rubin, Hunter & Ford 1991; Mendes de Oliveira &
Hickson 1994), that, relative to field galaxies, spirals tend to have low HI content (Williams
& Rood 1987), and that ellipticals have low velocity dispersion for their luminosity (Zepf &
Whitmore 1993). Hickson, Kindl & Huchra (1988) have also noted the existence of statistical
correlations in group properties, such as a tendency for low spiral fraction to be associated with
high velocity dispersion.
Despite this intensive observational study, and increasing theoretical interest, the very nature of compact groups is still unclear. Numerical simulations and theoretical arguments (e.g. Barnes 1984, 1985; Mamon 1987; Barnes 1989) indicate that, at the high densities inferred in compact groups, galaxies should merge within a few crossing times. In practice, the way in which compact groups are identified (i.e. through their high projected galaxy density) imposes strong selection effects which are likely to cause dynamical timescales to be underestimated (White 1990). However, these effects are hard to quantify, and Mamon (1986, 1987, 1995) has argued for several years that the difficulties of forming dense bound groups at the rate required to replace those lost through merging make it much more likely that the bulk of them are not truly dense in three dimensions. The observed peculiarities in the properties of HCG galaxies may still be explained if they contain real pairs, or occasionally triplets, which can interact (Mamon 1992a), whilst trends such as the relationship between spiral fraction and velocity dispersion could result from redshift-dependent selection effects (Mamon 1992b). A new twist has recently been added to the ‘chance superposition’ hypothesis by the suggestion of Hernquist, Katz & Weinberg (1995) (HKW95), that compact groups may be the result of looking along the filamentary arrangements of galaxies which are predicted by most cosmological simulations.

Meanwhile, recent numerical studies have suggested two ways in which compact groups could be continuously generated to replace those lost to the merging instability. Diaferio, Geller & Ramella (1994, 1995) (hereafter DGR94, DGR95) argue that compact configurations, most of which are bound, are formed continuously during the collapse and virialisation of larger groups – though it should be noted (Mamon, private communication) that they do not include the requirement of high projected galaxy density (< 26′′ arcsec^-2) applied by Hickson, when identifying ‘compact groups’ in their simulated data. Governato, Tozzi & Cavalieri (1995) (GTC95) note that the effects of continuing infall of surrounding galaxies onto an overdense region have been ignored in earlier studies, and show that this can regenerate real compact configurations after the galaxies in the initial collapsed group have merged.

Given the difficulties of small number statistics and projection effects associated with the galaxies in groups, an attractive option is to study hot gas trapped in the group potential, rather than just the galaxies themselves. In the case of galaxy clusters, this has proved a very successful approach, and the gas has turned out to constitute the bulk of the baryonic mass. The detection of significant quantities of hot gas associated with a group as a whole, would provide strong evidence for a genuine bound system, and one might hope to learn more about the dynamics and evolutionary history of groups by studying the properties of the gas in detail.

Given the velocity dispersion of compact groups (∼100-400 km s^-1), gas temperatures ∼0.1-1 keV are to be expected. Hence the gas is best studied in the soft X-ray region of the spectrum. Prior to the launch of ROSAT such studies were not feasible. However, the combination of high sensitivity, low background, and reasonable spatial resolution provided by the ROSAT Position Sensitive Proportional Counter (PSPC) has changed this situation, and several studies of the X-ray properties of individual groups (Mulchaey et al 1993; Ponman & Bertram 1993; David et al. 1994; Sulentic, Pietsch & Arp 1995) and collections of groups (Ebeling, Voges & Böhringer 1994 (EVB94); Pildis, Bregman & Evrard 1995 (PBE95); Saracco & Ciliegi 1995 (SC95); David, Jones & Forman 1995; Mulchaey et al. 1995; Henry et al. 1995) have now been published.

It is clear from these studies that some galaxy groups (both loose and compact) do contain hot X-ray emitting gas with T ∼ 1 keV, but beyond this, much of the evidence about the properties of this emission, and its correlation with other group properties, tends to be rather anecdotal, due to the lack of any sensitive survey with a reasonable level of completeness. This paper presents the results of the first such survey.
We have combined data from the ROSAT All Sky Survey (RASS) with deeper pointings, to produce an almost complete survey of the properties of the Hickson compact galaxy groups. This allows us to study the X-ray luminosity function of these groups, and to search for relationships between the X-ray luminosity and temperature and other group properties. The data and their reduction are described in section 2, and the results of the survey presented in sections 3-5, after which, in section 6, we consider the implications of our results for models of compact groups. Distances throughout the paper are derived assuming $H_0 = 50 \text{ km s}^{-1} \text{Mpc}^{-1}$.

2 DATA REDUCTION

The original catalogue of 100 Hickson groups (Hickson 1982) was reduced by Hickson et al. (1992) to 92 systems, by discarding those found to contain fewer than three galaxies with accordant redshifts. In addition, we have excluded from our analysis HCG60, HCG65 and HCG94, which appear to correspond to the cores of galaxy clusters (EBV94; Ramella et al. 1994; Ebeling, Mendes de Oliveira & White 1995), and HCG4 and HCG91, which are completely dominated in the PSPC by strong X-ray flux from active galaxies within the group. HCG25 and HCG54 have also been excluded since they appear to be contaminated by nearby point sources or background features in the RASS data.

It has become apparent (c.f. Ramella et al. 1994; Rood & Struble 1994; EBV94) that many compact groups are associated with larger scale structures. We have therefore retained in our study groups such as HCG5 and HCG48, which may be falling into clusters, and HCG58 which is apparently part of the larger galaxy group MKW10 (Williams 1985).

Our sample therefore consists of 85 groups, for all of which either pointed or survey observations with the ROSAT PSPC are available. This corresponds to 92% of the accordant Hickson groups. Some basic properties of these systems and of our X-ray data for them are given in Table 1. The first four columns, taken from Hickson et al. (1992) and Hickson (1993), show the HCG number, redshift, total number of accordant galaxies, and spiral fraction (treating S0 galaxies as non-spirals). In the next column we give the line-of-sight velocity dispersion derived from the values presented by Hickson et al. (1992), which were corrected for measurement errors. We have adjusted this velocity dispersion by a factor $\sqrt{N/(N-1)}$ (where $N$ is the number of group galaxies) to give an unbiased estimate.

All the accordant Hickson groups were observed by the ROSAT PSPC during the ROSAT All-Sky Survey, but exposure times were generally only a few hundred seconds. We have supplemented these observations with a total of 32 pointed observations, which have exposures typically an order of magnitude larger, and permit a much more sensitive analysis. The remaining columns in Table 1 give the origin of the data (survey or pointed), the exposure time, and the radius within which X-ray flux was gathered (see below).

The use of pointed data does not in practice introduce a serious selection bias into our results, since these observations were selected by a number of proposers using a variety of different criteria. Hence the pointed targets are not, more X-ray luminous than the average, for example. In nine cases, the pointing is serendipitous (i.e. the HCG was not the intended target), and in only three instances were groups known to be X-ray bright in advance of a pointed observation being proposed. In these cases we corrected for the bias when estimating the X-ray luminosity function (see the discussion in section 3).
2.1 Pointed data

Pointed observations were reduced in a standard way. An initial PSPC image was extracted, omitting data recorded during periods of high background flux (typically a few percent of each observation) and point sources identified using a likelihood source searching program (Allan, Ponman & Jeffries, in preparation). A spectral image (i.e. an $x,y,E$ data cube) covering the 0.1-2.4 keV band was then extracted for the vicinity of the group, and an estimate of the background subtracted from it. The latter was generated from a source-free region of the field (for most groups this was taken from the annulus $r = 0.6 - 0.7^\circ$, excluding any detected sources) and corrected to the position of the group using the known vignetting function of the instrument. Finally the background-subtracted spectral image was corrected for vignetting and divided by the exposure time, giving a map of the spectral flux.

Unrelated point sources identified in the first stage of the procedure were removed from the image to the 95% radius of the point spread function. In many groups, emission from individual galaxies was apparent. Our aim in the present survey is to study the X-ray emission from the hot intragroup gas – we therefore excluded flux from individual galaxies, except in the case of dominant ellipticals which appeared to be at the centre of the X-ray emission, since in this case it is more appropriate to identify the ‘galaxy’ emission with the hot gas in the core of the group potential (as seen in cD clusters). This applies in the case of the dominant galaxies HCG12a, HCG37a, HCG42a, HCG62a and HCG97a. In all other cases, galaxy emission was removed by excising a circle of radius typically $1.2^\prime$. Radial profiles of the flux from individual galaxies were examined to establish that this radius was satisfactory.

Except in the case of the two brightest groups, HCG62 and HCG97, it was found that X-ray emission was undetectable outside a radius corresponding to 200 kpc. This was therefore adopted as the standard metric radius within which the signal and spectrum was evaluated for each group. In the case of HCG62 and HCG97, a larger radius of 500 kpc was used.

The detected count rate within the metric radius was extracted and compared with the Poisson error from the background. Only sources exceeding a 3 sigma detection threshold are regarded as having detectable diffuse emission in the following analysis. For these groups, a spectrum was extracted by collapsing the region of the spectral image cube (excluding point sources) within the metric radius. This spectrum was then fitted with a hot plasma model (Raymond & Smith 1977) with an absorbing column frozen at the value derived from radio surveys of galactic H\textsc{i} (Stark \textit{et al.} 1992). The metallicity was generally left as a free parameter in these fits, but was often poorly constrained. In some cases it was necessary to fix its value (0.3 solar was adopted) in order to get a stable fit.

EVB94 noted the presence of some wisps of extremely soft emission in the vicinity of several Hickson groups, which they tentatively identified with portions of old supernova remnants within our own galaxy. We also encountered several cases in pointed data (HCG10, HCG18 and HCG31) in which we recorded an extremely soft signal, confined entirely to our bottom energy channel of 0.1-0.2 keV. In none of these cases was the source bright enough to image in order to determine its morphology. Due to the likelihood of contamination, we therefore treat these sources as non-detections. In the case of HCG33, we see a clear signal from the group, but this is accompanied by strong flux in the lowest energy band which is inconsistent with the high column ($N_{\text{H}} = 1.85 \times 10^{21} \text{ cm}^{-2}$) of the source. In this case we have excluded the bottom energy channel from the spectral fitting.
The fitted spectral model has been used in each case, to derive a bolometric X-ray luminosity for detected sources. The latter were corrected for the portions masked out to remove contaminating point sources, by replacing the ‘holes’ in the data with interpolated flux values. In the case of undetected sources, we have used a standard spectral model with temperature $T = 1\,\text{keV}$, metallicity $Z = 0.3\,\text{solar}$, and the appropriate galactic absorption column, to convert the flux limits to bolometric luminosities. The resulting parameters are listed for each group in Table 2.

### 2.2 Survey data

The RASS data at the positions of all accordant Hickson groups were analysed by EVB94 using a technique, known as VTP (Ebeling & Wiedenmann 1993), specially adapted to searching for extended emission. VTP gives an estimate of the source flux which is independent of the projected shape of the emission region. The percentage of the overall flux detected directly depends, however, on the surface brightness of the source, and corrections assuming a model profile have to be applied to recover the total flux. For the present study we have avoided this model dependence (except for the case of HCG51 – see below) by proceeding in the same way as for the above analysis of the pointed data – extracting flux estimates in the 0.1-2.35 keV band from a region of 200 kpc radius around the optical centre of each group.

The background in the vicinity of each group was derived from the VTP analysis (which effectively fits a Poisson distribution to the observed distribution of counts in the field, after removal of detected sources), and this then defines the background noise in the exposure. A 3 sigma detection threshold was applied, as in the pointed analysis, and a total of 18 accordant groups detected. However, several of these are contaminated by AGN or by probable foreground soft emission (see EVB94) or point sources, and in 6 cases we have higher quality pointed data. There remain five sources (HCG51,82,83,85 and 86) which are detected in the RASS data, but for which no PSPC pointed data are available. In addition, we derived 3 sigma count rate upper limits within $r = 200\,\text{kpc}$ for a further 48 groups.

The poor statistical quality of the RASS data does not permit any detailed spectral analysis, so, for both detected sources and for upper limits, we have converted count rates into bolometric luminosities using the same spectral model as for the pointed upper limits: a $T = 1\,\text{keV}$, $Z = 0.3\,\text{solar}$ Raymond & Smith plasma model, with the appropriate Stark column (given in Table 2). One exception was made to the use of a metric radius of 200 kpc in the RASS data; HCG51 is a very X-ray luminous group, and flux was detected by VTP out to a radius of at least 300 kpc. In this case we have therefore used the count rate derived by Ebeling et al., which was corrected for flux missed by the VTP algorithm using an assumed King profile. This is approximately double the luminosity within $r = 200\,\text{kpc}$.

### 3 SURVEY RESULTS AND PREVIOUS WORK

The derived bolometric luminosities and spectral properties of the 85 groups surveyed are given in Table 2. Note that the luminosities tabulated relate to diffuse emission from the groups only. Wherever emission appears to be related to a particular group galaxy, it has been removed (except in the case of dominant ellipticals) as discussed in section 2.1. There are some groups for which the statistical quality of the data, or the small size of the group, did not permit emission from galaxies to be identified and removed. These systems (8 in total) are flagged with
a quality value \( q = 2 \) in Table 2. Fully resolved systems are given quality flag 1, and upper limits are flagged with a ‘U’. In practice, the X-ray luminosities of most of the \( q = 2 \) systems are sufficiently high that the contamination from galaxy emission (typically a few \( \times 10^{40} \) erg s\(^{-1} \), judging from the resolved systems) is likely to be small.

It is interesting to compare the results in Table 2 with those of the smaller surveys of Hickson groups carried out by PBE95 and SC95. Each of these sets of authors analysed PSPC data for 12 HCGs (PBE95 also included the NGC2300 group of Mulchaey et al. in their sample). Both found some groups to contain hot gas with \( T \approx 0.7 - 1.0 \) keV. However there are significant differences between their results and ours.

The most striking difference relates to low surface brightness emission. One of the main conclusions of PBE95 was that diffuse X-ray emission is only detected in systems with spiral fractions less than 50\%, whereas we detect diffuse flux in several systems with high spiral content. This is a very important point, since it has a strong bearing on the questions of the reality of compact groups and the origin of the hot gas, as discussed in section 6 below. The most extreme example is HCG16, a system containing only spiral galaxies, which was studied by SC95. They concluded that there was no diffuse emission, whilst we detect emission with a low temperature (\( T = 0.30 \) keV), and a bolometric luminosity which is 32 times their quoted 0.5-2.3 keV upper limit!

There appear to be two reasons for this dramatic difference in results from the same data. SC95 (and also PBE95) tested for the presence of diffuse emission in groups by smoothing an image and looking for signs of extension. This is not a very sensitive test for low surface brightness emission. In addition, SC95 limited their data to the band 0.5-2.3 keV. Since we find that spiral-rich groups with diffuse emission tend to have low temperatures, discarding the lower energy channels will have significantly reduced their sensitivity to this emission.

To convince the reader that there is, in fact, extended X-ray emission in HCG16, we show in Fig.1 the radial profile of the PSPC surface brightness about the centre of the optical group, after emission from the individual galaxies (and unrelated point sources) has been removed. In the present case, the emission can actually be seen in a heavily smoothed image, as is shown in Fig.2 in which an adaptive smoothing algorithm (which smoothes low surface brightness areas more heavily than high brightness regions) has been applied to a 0.1-2.4 keV image of the group. Finally, in Fig.3 we show the PSPC spectrum of the diffuse emission (flux from the galaxies is excluded) with the best fitting hot plasma model overlaid.

In the case of PBE95, the authors appear to have been rather unlucky in their choice of groups, since we also find no detectable diffuse emission in their spiral-rich groups, despite our more sensitive test. In the luminous groups like HCG62, in which PBE95 detect extended emission, it is noticeable that their luminosities are considerably lower than ours. This is partly due to the fact that they exclude a region around the galaxies, whilst in the case of dominant central ellipticals we include this as part of the group emission, as described in section 2.1, but in addition, as they note themselves, the results are sensitive to the background level selected. In the case of HCG62, at least, they have adopted a background value which appears to be too high. An independent analysis of this group by David, Jones & Forman (1995) agrees well with our earlier results (Ponman & Bertram 1993).

4 DISTRIBUTIONS AND CORRELATIONS
4.1 Luminosity and temperature

The diffuse luminosity of our detected systems, and 3σ upper limits for the remainder of our sample, are plotted against their redshifts in Fig.4. Although we do not detect any of the high redshift HCGs, it is interesting to note that a group as luminous as HCG62 would have been detected at any redshift out to \( z \sim 0.1 \). This suggests that the high redshift HCGs in our sample (remembering that we have excluded three which we believe to be cluster cores) are unlikely to be misidentified clusters.

The X-ray luminosities of detected groups appear to be uncorrelated with either the number of galaxies in the group (which ranges from 3 to 7 within our detected sample) or the total optical luminosity. The lack of correlation with richness is not surprising if groups have been subject to significant merging, which would reduce the population, whilst probably increasing the amount of intragroup gas (due to galaxy winds driven by starburst activity), but the lack of any relationship between X-ray and optical luminosity, shown in Fig.5, is interesting. It strongly suggests that the hot gas is associated not with the galaxies, but with the potential well as a whole. It also indicates that the bulk of the gas did not originate from the galaxies.

In Fig.6, we show the distribution of \( L_X/L_B \) for the detected systems (\( L_B \) is taken from Hickson et al. 1992, and corrected to \( H_0 = 50\text{km s}^{-1}\text{Mpc}^{-1} \)). This should be compared with the typical value \( L_X/L_B \approx 10^{-4} \) for spiral and low luminosity elliptical field galaxies, whilst even for very bright ellipticals the ratio barely reaches \( 10^{-3} \) (Canizares, Fabbiano & Trinchieri 1987). Noting that most of the HCGs with the lowest values of \( L_X/L_B \) are dominated by spiral galaxies, it is apparent that the diffuse X-ray emission is too bright to be attributed to the member galaxies, even in the \( q = 2 \) cases where we have not been able to remove the galaxy contribution (unless previously unrecognised low luminosity active galactic nuclei are present).

Approximately 6% of the galaxies in Hickson groups are starburst galaxies (Zepf 1993), and it is well known that such galaxies can show extended X-ray emission arising from galactic winds (e.g. Fabbiano 1988). In the case of HCG16, three of the galaxies were detected by IRAS (Hickson et al. 1989), and two of them (HCG16c and HCG16d, on the left in Fig.2) have the warm far infrared (FIR) colours characteristic of starburst galaxies. However, comparison with other starburst and merging systems shows that the extended emission apparent in Fig.2 cannot be attributed simply to galactic winds. In normal starbursts like M82 and NGC253, detectable X-ray emission from winds extends only \( \sim 10 \text{kpc} \) from the galaxy, and even in the most luminous merging galaxies like Arp 220, it is limited to a few galactic radii; whilst in HCG16, its total extent is almost \( \sim 400 \text{kpc} \). In addition, there is a strong correlation between FIR and X-ray luminosities, which extends from normal to merging galaxies (Ponman & Read 1995). This predicts a luminosity in HCG16 which agrees well with the X-ray luminosity detected from the galaxies themselves, but is only one quarter of the observed luminosity of the whole system.

The distribution of temperature for the 16 groups for which we have been able to extract spectra of sufficient quality to fit a hot plasma model, is shown in Fig.7. Apart from two exceptionally cool groups (HCG15 and HCG16), the temperatures span only a factor of two, with most lying between 0.6 keV and 1 keV. This small range cannot be due to a temperature selection effect. For typical absorbing columns, the sensitivity of the ROSAT PSPC does not diminish greatly until \( T \) drops below 0.3 keV, and there is little change in count rate for a given emission measure as \( T \) rises from 1 to 2 keV. It seems that systems which look like compact groups are physically limited to a narrow range in \( T \) (apart from the cluster cores which we have rejected). Hotter systems would presumably be richer, and would fail Hickson’s isolation criterion. In order to
understand why cooler systems are not detected in any numbers, it is helpful to look at the relationship between X-ray temperature and luminosity.

The $L_X : T$ relation for our spectral subsample of 16 systems is shown in Fig.8. The two variables are significantly correlated: Kendall’s rank correlation coefficient (which is unit normal distributed) has a value of $K = 2.6$ ($P = 0.01$ of chance occurrence, from a two tailed test), and omitting the two $q = 2$ sources from the spectral sample, this rises to $K = 3.2$ ($P = 0.001$). A regression line has been fitted to the HCG points in Fig.8. It is important to allow for the errors in both luminosity and temperature when regressing, since neither are negligible, so we have used the doubly weighted regression technique discussed by Feigelson & Babu (1992), and made available through the ODRPACK package. This gives the relationship between bolometric X-ray luminosity and temperature:

$$\log L_X = (43.17 \pm 0.26) + (8.2 \pm 2.7) \log T.$$  

This relationship, which is very steep, is marked with its $1\sigma$ error envelope, in Fig.8.

In order to compare the trends in $L$, $T$ and later $\sigma$, with those seen in clusters, we have defined a set of clusters with high quality spectral data, which are also plotted on the figure. These ten clusters are those common to the samples of Edge & Stewart (1991), from where we take the bolometric luminosity and galaxy velocity dispersion, and Yamashita (1992) who gives temperatures and metallicities derived with Ginga and (in the case of the the Perseus cluster) Tenma. The relevant parameters for these clusters are shown in Table 3.

A best fit to the cluster $L : T$ relation has recently been derived by White et al. (in preparation) by applying doubly weighted regression to a large sample of clusters. They find, in our units, $\log L_X = 42.86 + 2.81 \log T$, which is marked as a heavy dashed line in Fig.8. This line passes above most of the galaxy groups, and is much flatter than the best fit trend for the HCGs. Fitting a regression line to the sample of clusters plus HCGs shown in Fig.8 gives the relation:

$$\log L_X = (42.62 \pm 0.13) + (3.29 \pm 0.17) \log T,$$

which is marked as the heavy solid line in the figure.

The steep $L : T$ relation for groups suggests a reason for the lack of many cool groups in our sample. There is clearly a great deal of scatter about the mean trend, and the two low $T$ groups which are detected both fall well above the regression line. Typical groups with $T < 0.5$ keV, would according to the regression, have luminosities below our detection limit of $\sim 10^{41}$ erg s$^{-1}$.

### 4.2 Galaxy morphology

As has already been noted by the authors of previous studies of the X-ray properties of samples of groups (EVB94; PBE95; SC95; Mulchaey et al. 1995; Henry et al. 1995), there is a relationship between X-ray luminosity and galaxy morphology. In Fig.9, we show the distribution of luminosity for detected groups, broken down into two classes according to whether the brightest galaxy is of early or late type. It can be seen that the brightest systems (those with $L_X > 4 \times 10^{42}$ erg s$^{-1}$) are all dominated by early-type galaxies.

To assess the significance of any difference between the diffuse X-ray luminosities of HCGs with brightest Sp and E/S0 galaxies, it is desirable to use not only the luminosities of detected
systems, but also the upper limits. This can be done using ‘survival analysis’, provided that
the sampling is ‘random’, in the sense that the limits are unrelated to the actual values of
the parameter being censored. For example, this requirement would not be met in a case where
longer observations are made for fainter sources, in an effort to detect them. Since we are dealing
with luminosities, the actual limits are determined by both exposure time and source distance.
In the case of our survey, the observation times were determined in almost all cases without any
knowledge of the X-ray brightness of particular sources, and in the absence of strong evolution,
the source distance is also unrelated to intrinsic luminosity. Random censoring is therefore a
good assumption.

We have used the ASURV package (Feigelson & Nelson 1985; Isobe, Feigelson & Nelson 1986),
which computes the significance of the difference between two distributions using a rank statistic,
which reduces to the Wilcoxon statistic in the uncensored case. Three different options are
available for the weights attributed to the censored values: the Gehan, logrank, and Peto &
Prentice statistics (Feigelson & Nelson 1985). These tests are most reliable when the two samples
being compared are comparable in size, and are censored in similar ways, both of which are true
in the present case. All three statistics find the luminosity distributions of HCGs dominated by
early and late type galaxies to differ, with significances of 99%, 96% and 98% respectively, for
the three tests.

As far as the morphological mix in the groups’ galaxy population is concerned, we find only
a very weak anticorrelation \( (K = -1.3, P = 0.2) \) between \( L_X \) and spiral fraction, \( f_{sp} \), in our
sample, as can be seen in Fig.10. This contrasts with earlier strong statements made on the
basis of smaller samples. Fig.10 shows a considerably stronger relationship \( (K = -2.3, P = 0.02) \)
between \( f_{sp} \) and \( T \). Since \( T \) indicates the depth of the potential, whilst \( L_X \) reflects the amount
of gas trapped in it, these results suggest that galaxy morphology is related to the overall mass
density in a group.

4.3 Velocity dispersion

A fairly strong relationship between luminosity and velocity dispersion \( (K = 1.8, P = 0.07 \) –
rising to \( K = 2.5, P = 0.01 \) if the eight \( q = 2 \) groups are excluded) can be seen in Fig.11.
The plotted errors in \( \sigma \) are dominated by the statistical uncertainty in determining a velocity
dispersion from only a handful of galaxies. Again, we can obtain a better indication of the
significance of this relationship by taking into account the censored luminosity values shown in
the figure. Using both the Cox proportional hazard model, and the generalised Kendall rank
correlation statistic, adapted for censored data as described by Isobe, Feigelson & Nelson (1986),
we find the correlation between \( L_X \) and \( \sigma \) to be significant at \( > 99.9\% \) confidence from either
test.

A 2D regression on \( \log L_X \) and \( \log \sigma \), using the errors in both, gives

\[
\log L_X = (30.0 \pm 5.1) + (4.9 \pm 2.1) \log \sigma,
\]

using all 22 detected HCGs. As can be seen from Fig.12, this is in reasonable agreement with an
extension of the trend found from clusters, shown as a dashed line: \( \log L_X = 25.45 + 6.92 \log \sigma \),
(White et al. in preparation); though some flattening of the cluster trend may be indicated. A
best fit through our group + cluster sample gives

\[
\log L_X = (27.6 \pm 1.4) + (5.9 \pm 0.5) \log \sigma.
\]
This result may be compared to the report of Dell’Antonio, Geller & Fabricant (1994), from a study of X-ray and optical results for groups and clusters, of marginal evidence that the $L : \sigma$ relation may flatten below $\log \sigma \approx 2.5$. Dell’Antonio et al. note that they did not remove the contribution of galaxies to the X-ray emission, and suggest that this may be the cause of the change in slope. We have removed the galaxy contribution, and although our best fit to the group trend is somewhat flatter than the cluster relation, the difference is not statistically significant.

There is some indication ($K = 1.6, P = 0.1$) of a correlation between $\sigma$ and $T$ in the HCG spectral sample (Fig.13), and the comparison with clusters makes the trend clear. The $\sigma : T$ relation for clusters is consistent with a value for $\beta$, the ratio of specific energy in galaxies to that in the gas, of unity. However, it is clear that most groups have $\beta < 1$, i.e. they fall to the high $T$/low $\sigma$ side of the $\beta = 1$ line. The median value of $\beta$ for our HCG sample is 0.47 — the specific energy in the gas is higher than that in the galaxies. The trend towards lower $\beta$ in smaller systems is in agreement with the results of Bird, Mushotzky & Metzler (1995), who study a sample of clusters specially corrected for the effects of substructure on velocity dispersion, and find $\sigma \propto T^{0.61 \pm 0.13}$. A regression through our group + cluster sample gives

$$\log \sigma = (2.54 \pm 0.04) + (0.55 \pm 0.05) \log T,$$

which is shown as a solid line in Fig.13.

### 4.4 Metallicity

As can be seen in Table 2, the metallicity derived in cases where statistics were sufficiently good to allow a fit, is in many cases considerably lower than the value of 0.3-0.4 solar found in most rich clusters. The distribution of derived HCG metallicities is shown in Fig.14, but note from Table 2 that the values above 0.4 mostly have large errors, and the overall weighted mean metallicity of the sample is only 0.18 solar.

This result is surprising given the trend seen in clusters (e.g. Arnaud 1994) for higher metallicity in cooler systems, which would lead one to expect typical metallicities $\approx$0.6 solar in systems with $T \sim 1$ keV. The low metallicities found here are in accord with most previous ROSAT studies of hot gas in galaxy groups (see e.g. the compilation in Mulchaey et al 1995). However, we believe that at present this result should be viewed with caution, since ROSAT is unable to resolve individual emission lines, and inferred metal abundances rely heavily on the assumption that the continuum is correctly modelled as an isothermal hot plasma. When temperature variations in the gas are taken into account, metallicities several times higher are found to be consistent with the data (Bourner & Ponman, in preparation). On the other hand, in the poor group containing NGC2300, the low abundance ($\approx$0.1 solar) can be resolved over a range of radial elements, and is also supported by ASCA observations, which have the advantage of much higher spectral resolution (Davis et al. 1995).

### 5 THE X-RAY LUMINOSITY FUNCTION

The HCG catalogue starts to become incomplete for total group magnitudes $B_T > 14$ (Hickson, Kindl & Auman 1989), and the high redshift tail of the catalogue represents a biased subset with particularly luminous galaxies, high velocity dispersion and low spiral fraction (Whitmore 1990). It is also more difficult to determine galaxy morphology in the higher redshift groups,
and all three of the groups we reject as being likely cluster cores lie at $z > 0.04$. To avoid possible biases, we therefore base our analysis of the X-ray luminosity function of HCGs on the subsample of 62 of the 85 groups in our survey with $z < 0.04$. We detect diffuse emission from 18 of these systems. Since we know the distribution of $3\sigma$ upper limits for this set of 62 pointings, we can estimate the fraction of groups in each luminosity bin which show detectable diffuse emission as

$$f(L_i) = \frac{N(L_i)}{N_{lim}(\leq L_i)},$$

where $N(L_i)$ is the number of detected systems in the $i$th luminosity bin, and $N_{lim}(\leq L_i)$ is the number of groups in the sample with $3\sigma$ detection limits $\leq L_i$.

We applied a small correction to $N_{lim}(\leq L_i)$, to allow for the fact that three of the long observations, of HCG42, HCG92 and HCG97, were made with prior knowledge that the groups were bright. These three observations were accordingly not available for the detection of faint systems, and to include them in $N_{lim}(\leq L_i)$ for low values of $L_i$ would therefore give an underestimate of $f(L_i)$. This has been allowed for by including these three pointings in $N_{lim}(\leq L_i)$ as though the limiting sensitivity of each was the actual luminosity of the group concerned.

The resulting frequency distribution for a series of logarithmic luminosity bins is shown in Fig.15a, and the cumulative distribution in Fig.15b. The lowest populated luminosity bin plotted is likely to underestimate the true frequency of occurrence of diffuse emission, since one should really divide $N(L_i)$ by the number of systems with detection thresholds for diffuse emission $\leq L_i$, whereas we are using detection thresholds for total X-ray emission. In the lowest bin, the galaxy contribution to $L_X$ may be quite significant, so we overestimate $N_{lim}(\leq L_i)$, and underestimate $f(L_i)$.

From Fig.15b, our best estimate of the total fraction of HCGs with diffuse luminosity $L_X > 10^{41.1}$ erg s$^{-1}$, is $0.86 \pm 0.25$, where the error arises from Poisson fluctuations in the number of detected systems, and is dominated by uncertainties in the frequency of low $L_X$ systems. The fraction of HCGs with luminosities in excess of $10^{42}$ erg s$^{-1}$ is $0.20 \pm 0.07$. Monte Carlo simulations, using sources with luminosities drawn at random from a known distribution, confirmed that the procedure above gives an unbiased estimate of the fraction of systems with luminosity above a chosen threshold, and that the calculated errors are realistic.

Alternatively, if one makes the assumption of random censoring (see section 4.2) then the luminosity function can be estimated using the Kaplan-Meier estimator (Feigelson & Nelson 1985). This gives a value of 0.75 for the fraction of groups with $L_X > 10^{41.1}$ erg s$^{-1}$.

One respect in which the sample of accordant Hickson groups is less than satisfactory, is that groups with 3 or more accordant galaxies have been retained in the sample, even though Hickson’s original selection criterion required four members. (For consistency one should really go back and repeat the whole search process with a threshold of three member galaxies.) If we exclude those groups in our sample with only three accordant members, we reduce the sample at $z < 0.04$ from 62 to 45, of which 17 are detected. Repeating the analysis as before, we estimate that the fraction of HCGs groups with $\geq 4$ accordant members which have diffuse emission above our threshold of $L_X = 10^{41.1}$ erg s$^{-1}$ is $1.06 \pm 0.32$ – i.e. all of them! An analysis using the Kaplan-Meier estimator gives an estimated fraction of 0.85 above the threshold in this case. These large fractions have important implications for the reality of compact groups, as will be discussed in the next section.

Mendes de Oliveira & Hickson (1991) have used the statistically homogenous sample of HCGs with $\geq 4$ accordant members to estimate a space density for these systems. Using simulations
to correct for selection effects, they obtain a density of $4.9 \times 10^{-6} \text{ Mpc}^{-3}$ (for $H_0 = 50$). We can use this, together with our results, to construct an X-ray luminosity function for these systems. This is shown in Fig.16, and compared to two estimates of the cluster luminosity function, extrapolated down to low luminosity systems.

The best available estimate of the local cluster X-ray luminosity function (XLF), is that derived from the flux limited ROSAT Brightest Cluster Sample, by Ebeling et al. (1996). This is well described by a Schechter function, which is shown as a solid line in Fig.16. Also shown (dotted) is the 1σ error envelope for the simple power law cluster XLF derived from the smaller sample of clusters available from the Einstein Medium Sensitivity Survey (the lowest redshift shell, $z = 0.14-0.20$) by Henry et al. (1992). Note that the Henry et al. function has to be extrapolated by over an order of magnitude in $L_X$ (the lowest luminosity in their cluster sample is $\sim 10^{44} \text{ erg s}^{-1}$) and hence has a rather large associated error, whilst the Ebeling et al. sample extends down to $L_X \sim 10^{43} \text{ erg s}^{-1}$.

The cluster results actually apply to the energy bands 0.3-3.5 keV (Henry et al.) and 0.1-2.4 keV (Ebeling et al.), whilst our luminosities are bolometric; however, for typical HCG spectra, restriction to either of these bands would reduce our luminosities by only $\sim 20-30\%$. Henry et al. (1995) have recently derived a point on the XLF for loose galaxy groups, using RASS data from a region around the North Ecliptic Pole, where the survey exposure was greatest. This point (plotted in Fig.16) fits quite well on an extrapolation of the Henry et al. (1992) XLF, however it based on a very small sample (3 groups) and its statistical error gives an overoptimistic impression of its reliability, due to the possible influence of large scale structure. Larger surveys of loose groups are required to establish the behaviour of the cluster XLF for poor systems.

We have determined the slope of the HCG luminosity function by regressing on the errors in $n(L)$, omitting the lowest bin, which is expected to be underestimated, as explained above. This gives

$$\log n(L) = (69.0 \pm 9.9) - (1.74 \pm 0.23) \log L_X,$$

with a slope very similar to that ($\alpha = 1.78 \pm 0.09$) of Ebeling et al., but marginally flatter than that ($\alpha = 2.19 \pm 0.21$) derived by Henry et al. (1992). Comparing with the more reliable XLF of Ebeling et al., it appears that the HCGs account for approximately 4% of the X-ray luminosity of galaxy groups as a whole. For comparison, Mendes de Oliveira &Hickson (1991) estimate that galaxies in HCGs account for approximately 0.8% of the total galactic light in the local Universe.

6 DISCUSSION

HCGs are undoubtedly to some extent a heterogeneous collection. With the availability of galaxy redshifts, eight of the original 100 groups have already proved to be chance projections (Hickson et al. 1992), and several more appear to be really cluster cores. The interesting question is, what are most of them? The observed peculiarities of HCG properties demonstrate that they cannot be chance projections of field galaxies, and theoretical studies show that rather few of them are likely to be isolated bound configurations with ages of more than a few Gyr, since this should result in very substantial merging, leading to a large dominant merger remnant (e.g. Barnes 1989) which is not generally observed (Mamon 1995).
However, there remain at least four credible pictures against which we can measure our results. Most HCGs could be real bound systems which are (i) created by collapse of subsystems within larger groups (DGR94, DGR95), or (ii) are single systems refreshed by continuing infall of new galaxies from the surrounding field (GTC95). Alternatively, they could mostly be (iii) chance projections of galaxies within looser groups or clusters (Mamon 1986), or (iv) unbound filamentary structures viewed along their length (HKW95).

The most immediately striking result of the survey reported above is the high fraction (> 75%) of HCGs inferred to show diffuse X-ray emission, once one corrects for visibility factors in a largely complete sample. This contrasts with the typical values of ~ 30% inferred in previous studies from the detection rate without such correction. This poses a problem for the ‘filament hypothesis’. If HCGs are mostly filaments several Mpc in length, then the X-ray surface brightness we observe, even in the fainter groups, requires the filaments to contain hot gas with \( T \sim 1 \) keV and particle density \( n \sim 10^{-4} \text{ cm}^{-3} \) (the length of such a filament along our line-of-sight is determined by the galaxy velocity dispersion, which in this picture arises from the Hubble flow). HKW95 mention the possibility of shock heated gas within the filaments, but give no details of the densities expected. Briel & Henry (1995) have recently searched for X-ray filaments between neighbouring clusters and obtain 2\( \sigma \) upper limits corresponding to \( n = 5 \times 10^{-5} - 10^{-4} \text{ cm}^{-3} \), for assumed temperatures of 0.5-1 keV.

The filament hypothesis also has no obvious explanation for the correlations between \( L_X \), \( T \), velocity dispersion and spiral fraction, reported above. It appears, therefore, that it can be ruled out, except for the < 25% of HCGs which show no diffuse X-ray emission. Ostriker, Lubin & Hernquist (1995) conclude from the relative luminosities of groups and clusters in the X-ray and optical bands, that there is evidence that either many apparently compact groups are elongated along the line-of-sight, or that smaller systems are relatively gas poor. However, David, Jones & Forman (1995) show that the gas fraction does indeed increase with system size, and in view of our results, this seems the most likely explanation for the trends noted by Ostriker et al.

The idea of chance alignments within loose groups is more difficult to eliminate, since some loose groups also exhibit diffuse X-ray emission with properties rather similar (Mulchaey et al. 1995) to those of HCGs. The fact that the HCG luminosity function is not very different in slope to the cluster-group XLF is also consistent with the idea that one is seeing just a chance subset of the loose groups, viewed at a fortuitous angle. Even if the flatter slope of the HCG function were a robust result, one could always argue that selection effects make the appearance of compact projections more likely within loose groups with denser cores, which would probably be more luminous than the average. However, under the projection hypothesis the HCG galaxies are a random sample taken from the larger loose group membership, and it therefore becomes difficult to explain why one sees the rather pronounced relationships between X-ray and galaxy properties manifested in the different luminosity distributions for spiral and elliptical dominated HCGs (Fig.9), or the correlation between \( T \) and \( f_{sp} \) (Fig.10b).

In addition, the lack of any relationship between \( L_X \) and \( L_B \) suggests strongly that we must be seeing a genuine potential well. This does not rule out a loose group, but it does imply that it would have to be collapsed, whereas Mamon (1994) argues that the great majority of loose groups are still in the early stages of collapsing.

Our results therefore lend strong support to the idea that most HCGs are genuinely compact systems, though not necessarily fully virialised (c.f. the X-ray morphology of HCG16). In terms of discriminating between the two models for the formation of such groups, we note that DGR95 predict from their models of compact group formation within looser groups, that the \( L : T \) and
$L : \sigma$ relations for HCGs should be much flatter than those seen in clusters – they obtain $L \propto T^{0.68} \propto \sigma^{0.57}$. The relations we observe are much steeper than this. However, DGR95's models lack some important and relevant astrophysics, notably galaxy winds, so it is not clear that this disagreement is an insuperable problem for their basic picture, which agrees well with the observation that many HCGs are embedded in larger structures.

The fact that HCGs seem to fall rather nicely onto the $L:\sigma$ trend for clusters does suggest that they are most likely to be self-contained virialised systems (albeit with continuing infall). However, there does seem to be one major problem with the model of GTC95. It predicts the presence of a dominant merger remnant, from the early collapse and merger of the perturbation which seeded the present group. It has already been pointed out by Mendes de Oliveira & Hickson (1991) that the difference in magnitude between first and second ranked galaxies in HCGs is no different for groups with dominant ellipticals (such as would be produced by merging) than for dominant spirals – although it appears that selection effects have played a part in reducing the number of systems with dominant galaxies identified as HCGs (Prandoni, Iovino & MacGillivray 1994). In addition, we note that although the four brightest HCGs in our detected sample have elliptical first ranked galaxies, in only one of these (HCG51) is the brightest galaxy more than twice as optically luminous as the second ranked galaxy. If the picture of a long lasting virialised core is to be retained, then it appears that some way round the merging instability needs to be found. On the other hand, the fact that X-ray luminosity seems to be correlated rather strongly with the morphology of the first ranked galaxy, but much more weakly to the overall fraction of early-type galaxies in a group, does suggest that some merging has occurred in the more luminous systems.

Finally, it is interesting to consider the possible reasons for the steepening of the $L : T$ relation at $T \sim 1$ keV seen in Fig. 8. Since low $T$ corresponds, through the virial theorem, to a shallow potential well, the most obvious interpretation is that energy injection from galaxies (which have internal velocity dispersions similar to those of galaxies within a group) might have a substantial effect on groups, whilst being insignificant in rich clusters. The main effect of energy injection into the intracluster medium is to reduce the gas density in the central regions, and hence the X-ray luminosity (Metzler & Evrard 1994). Since this effect is much more pronounced in smaller mass systems, and some gas may even escape from the well altogether (Renzini et al. 1993), the effect is to steepen the $L : T$ relation at low temperatures (Knight & Ponman, in preparation). If this interpretation is correct, then the large scatter about the mean $L : T$ trend apparent in Fig. 8 must be due primarily to differences in the wind injection history of different groups.

Vigorous wind injection also has a more modest effect on the gas temperature, which is raised by the injection of extra high entropy gas. Bird, Mushotzky & Metzler (1995) suggest that this, together with some reduction in velocity dispersion due to the more effective action of dynamical friction in low mass systems, is responsible for the lower value of $\beta$ in smaller systems, as reported in section 4.3.

7 SUMMARY

From our survey, covering 92% of the accordant Hickson compact groups, we deduce that at least three quarters of these systems exhibit detectable X-ray emission from hot intragroup gas. In most cases, the luminosity of this diffuse emission is considerably higher than that arising from individual galaxies. We find that the HCGs account for $\approx 4\%$ of the X-ray luminosity density of
galaxy groups, and have a luminosity function similar to the cluster XLF.

We have investigated the spectral properties of the diffuse X-rays, and find that the temperature is confined to a rather narrow band (0.5-1.0 keV in most cases), even though the luminosity ranges over two orders of magnitude. This represents a considerable steepening of the cluster $L : T$ relation below $T \sim 1$ keV, which may result from the action of galaxy winds.

The low metallicity apparent from our spectral fits (typically 0.2 solar for our sample as a whole) is not yet a secure result, given the possibility of a downward bias arising from fitting single temperature models to multi-temperature gas. If it is confirmed by observations with higher resolution X-ray spectrometers, then it implies that the majority of the gas in the group wells is primordial, and the fact that it falls below the metallicity of most rich clusters has interesting implications for the evolution of galaxies and the intracluster medium, and will place limits on the amount of wind injection which can be invoked.

The properties of the X-ray emission are not strongly related to the luminosity or number of galaxies in a group, but they are related to galaxy morphology, with elliptical-rich systems being typically both brighter and hotter. However, earlier reports that spiral-rich systems show no diffuse X-ray emission are found to be incorrect. Emission is certainly present in some such systems, but it tends to be of lower surface brightness.

We argue that the high incidence of diffuse X-ray emission and the strong correlations of $L_X$ with $\sigma$ and $T$ rule out the possibility that most HCGs could be cosmic filaments viewed at a fortuitous inclination, and strongly support the idea that they are genuinely compact systems.

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Table 1. Basic properties of the 85 groups surveyed and the data obtained.

| HCG | $z$  | $N_{\text{gal}}$ | $f_{\text{sp}}$ | log$\sigma$ (km s$^{-1}$) | Pointed/Survey | $t_{\text{exp}}$ (s) | $r$ (kpc) |
|-----|------|------------------|-----------------|---------------------------|----------------|---------------------|----------|
| 1   | 0.0339 | 4 | 0.500 | 1.94 | S | 396 | 200 |
| 2   | 0.0144 | 3 | 1.000 | 1.73 | P | 18429 | 200 |
| 3   | 0.0255 | 3 | 0.333 | 2.48 | P | 7856 | 200 |
| 5   | 0.0410 | 3 | 0.333 | 2.24 | S | 283 | 200 |
| 6   | 0.0379 | 4 | 0.500 | 2.45 | S | 387 | 200 |
| 7   | 0.0141 | 4 | 0.750 | 1.98 | S | 300 | 200 |
| 8   | 0.0545 | 4 | 0.000 | 2.71 | S | 450 | 200 |
| 10  | 0.0161 | 4 | 0.750 | 2.38 | P | 13861 | 200 |
| 12  | 0.0485 | 5 | 0.200 | 2.43 | P | 8784 | 200 |
| 13  | 0.0411 | 5 | 0.200 | 2.25 | S | 447 | 200 |
| 14  | 0.0183 | 3 | 0.667 | 2.61 | S | 437 | 200 |
| 15  | 0.0228 | 6 | 0.500 | 2.66 | P | 14029 | 200 |
| 16  | 0.0132 | 4 | 1.000 | 2.13 | P | 14852 | 200 |
| 17  | 0.0603 | 5 | 0.000 | 1.99 | S | 262 | 200 |
| 20  | 0.0484 | 5 | 0.000 | 2.48 | S | 450 | 200 |
| 21  | 0.0251 | 3 | 0.667 | 2.12 | S | 259 | 200 |
| 22  | 0.0090 | 3 | 0.667 | 1.10 | P | 12211 | 200 |
| 23  | 0.0161 | 4 | 0.750 | 2.26 | P | 4119 | 200 |
| 24  | 0.0305 | 5 | 0.200 | 2.32 | S | 225 | 200 |
| 26  | 0.0316 | 7 | 0.571 | 2.31 | P | 4914 | 200 |
| 27  | 0.0874 | 4 | 0.250 | 1.92 | S | 350 | 200 |
| 28  | 0.0380 | 3 | 0.333 | 1.78 | S | 266 | 200 |
| 29  | 0.1047 | 3 | 0.000 | 2.70 | S | 246 | 200 |
| 30  | 0.0154 | 4 | 0.750 | 1.86 | S | 525 | 200 |
| 31  | 0.0137 | 3 | 1.000 | 1.67 | P | 2428 | 200 |
| 32  | 0.0408 | 4 | 0.000 | 2.37 | S | 391 | 200 |
| 33  | 0.0260 | 4 | 0.250 | 2.24 | P | 4012 | 200 |
| 34  | 0.0307 | 4 | 0.500 | 2.56 | S | 310 | 200 |
| 35  | 0.0542 | 6 | 0.167 | 2.54 | P | 15669 | 200 |
| 37  | 0.0223 | 5 | 0.400 | 2.65 | P | 4803 | 200 |
| 38  | 0.0292 | 3 | 1.000 | 0.96 | P | 3754 | 200 |
| 39  | 0.0701 | 4 | 0.500 | 2.34 | S | 321 | 200 |
| 40  | 0.0223 | 5 | 0.600 | 2.21 | P | 3642 | 200 |
| 42  | 0.0133 | 4 | 0.000 | 2.38 | P | 12791 | 200 |
| 43  | 0.0330 | 5 | 0.600 | 2.39 | S | 373 | 200 |
| 44  | 0.0046 | 4 | 0.750 | 2.16 | P | 4672 | 200 |
| 45  | 0.0732 | 3 | 0.667 | 2.34 | S | 626 | 200 |
| 46  | 0.0270 | 4 | 0.000 | 2.57 | S | 432 | 200 |
| 47  | 0.0317 | 4 | 0.750 | 1.45 | S | 448 | 200 |
| 48  | 0.0094 | 3 | 0.333 | 2.55 | P | 12358 | 200 |
| 49  | 0.0332 | 4 | 0.750 | 1.35 | S | 743 | 200 |
| 50  | 0.1392 | 5 | 0.000 | 2.72 | P | 1783 | 200 |
| HCG | z     | $N_{\text{gal}}$ | $f_{\text{sp}}$ | $\log \sigma$ (km s$^{-1}$) | Pointed/Survey | $t_{\text{exp}}$ (s) | $r$ (kpc) |
|-----|-------|------------------|-----------------|-----------------------------|----------------|-------------------|---------|
| 51  | 0.0258| 5                | 0.400           | 2.42                        | S              | 290               | >300    |
| 52  | 0.0430| 1                | 1.000           | 2.32                        | S              | 435               | 200     |
| 53  | 0.0206| 3                | 0.667           | 1.85                        | S              | 451               | 200     |
| 55  | 0.0526| 4                | 0.000           | 2.34                        | S              | 801               | 200     |
| 56  | 0.0270| 5                | 0.200           | 2.26                        | S              | 431               | 200     |
| 57  | 0.0304| 7                | 0.429           | 2.45                        | P              | 3226              | 200     |
| 58  | 0.0207| 5                | 0.600           | 2.25                        | P              | 11412             | 200     |
| 59  | 0.0135| 4                | 0.750           | 2.33                        | S              | 443               | 200     |
| 60  | 0.0130| 3                | 0.333           | 2.01                        | S              | 492               | 200     |
| 62  | 0.0137| 4                | 0.000           | 2.51                        | P              | 18028             | 500     |
| 63  | 0.0311| 3                | 1.000           | 2.01                        | S              | 308               | 200     |
| 64  | 0.0360| 3                | 0.667           | 2.40                        | S              | 314               | 200     |
| 66  | 0.0699| 4                | 0.000           | 2.54                        | S              | 567               | 200     |
| 67  | 0.0245| 4                | 0.500           | 2.38                        | P              | 16193             | 200     |
| 68  | 0.0080| 5                | 0.200           | 2.23                        | P              | 11865             | 200     |
| 69  | 0.0294| 4                | 0.500           | 2.40                        | S              | 424               | 200     |
| 70  | 0.0636| 4                | 1.000           | 2.13                        | S              | 497               | 200     |
| 71  | 0.0301| 3                | 1.000           | 2.70                        | S              | 515               | 200     |
| 72  | 0.0421| 4                | 0.250           | 2.48                        | S              | 414               | 200     |
| 73  | 0.0449| 3                | 0.667           | 1.98                        | P              | 4557              | 200     |
| 74  | 0.0399| 5                | 0.000           | 2.54                        | S              | 285               | 200     |
| 75  | 0.0416| 6                | 0.500           | 2.46                        | S              | 243               | 200     |
| 76  | 0.0340| 7                | 0.286           | 2.41                        | S              | 283               | 200     |
| 79  | 0.0145| 4                | 0.250           | 2.18                        | P              | 4890              | 200     |
| 80  | 0.0310| 4                | 1.000           | 2.49                        | S              | 1290              | 200     |
| 81  | 0.0499| 4                | 0.250           | 2.25                        | S              | 553               | 200     |
| 82  | 0.0362| 4                | 0.500           | 2.85                        | S              | 675               | 200     |
| 83  | 0.0531| 5                | 0.400           | 2.70                        | S              | 491               | 200     |
| 84  | 0.0556| 5                | 0.200           | 2.33                        | P              | 37490             | 200     |
| 85  | 0.0393| 4                | 0.000           | 2.62                        | S              | 2370              | 200     |
| 86  | 0.0199| 4                | 0.000           | 2.48                        | S              | 290               | 200     |
| 87  | 0.0296| 3                | 0.667           | 2.01                        | S              | 444               | 200     |
| 88  | 0.0201| 4                | 1.000           | 1.25                        | S              | 421               | 200     |
| 89  | 0.0297| 4                | 1.000           | 1.54                        | S              | 448               | 200     |
| 90  | 0.0088| 4                | 0.500           | 2.04                        | P              | 13518             | 200     |
| 92  | 0.0215| 4                | 0.750           | 2.65                        | P              | 15737             | 200     |
| 93  | 0.0168| 4                | 0.500           | 2.37                        | P              | 14784             | 200     |
| 95  | 0.0396| 4                | 0.750           | 2.54                        | S              | 443               | 200     |
| 96  | 0.0292| 4                | 0.750           | 2.16                        | P              | 2423              | 200     |
| 97  | 0.0218| 5                | 0.400           | 2.61                        | P              | 12050             | 500     |
| 98  | 0.0266| 3                | 0.000           | 2.16                        | S              | 402               | 200     |
| 99  | 0.0290| 5                | 0.200           | 2.46                        | S              | 364               | 200     |
|100  | 0.0178| 3                | 1.000           | 2.00                        | S              | 442               | 200     |
Table 2. X-ray properties of the surveyed groups. Distances assume $H_0 = 50$ km s$^{-1}$ Mpc$^{-3}$ and $N_H$ values are derived from radio surveys. Temperatures and metallicities were fixed at 1.0 keV and 0.3 solar (suffix F) in cases where data were inadequate to allow a fit. Errors are one sigma, and upper limits three sigma. The values marked with a dagger were too poorly constrained to allow errors to be derived. The quality flag is discussed in the text.

| HCG | d (Mpc) | $N_H$ ($10^{20}$cm$^{-2}$) | $T$ (keV) | Z (solar) | Qual | log $L_X$ (erg s$^{-1}$) |
|-----|--------|-----------------|----------|---------|------|-----------------|
| 1   | 203    | 3.67            | 1.0F     | 0.3F    | U    | <42.42          |
| 2   | 86     | 3.70            | 1.0F     | 0.3F    | U    | <41.28          |
| 3   | 152    | 3.18            | 1.0F     | 0.3F    | U    | <41.71          |
| 5   | 245    | 4.05            | 1.0F     | 0.3F    | U    | <42.54          |
| 6   | 227    | 3.50            | 1.0F     | 0.3F    | U    | <42.43          |
| 7   | 85     | 2.23            | 1.0F     | 0.3F    | U    | <42.03          |
| 8   | 327    | 3.95            | 1.0F     | 0.3F    | U    | <42.55          |
| 10  | 97     | 4.53            | 1.0F     | 0.3F    | U    | <41.43          |
| 12  | 291    | 3.69            | 0.89±0.12| 0.3F    | 1    | 42.31±0.08      |
| 13  | 246    | 3.30            | 1.0F     | 0.3F    | U    | <42.40          |
| 14  | 110    | 2.07            | 1.0F     | 0.3F    | U    | <42.02          |
| 15  | 137    | 2.72            | 0.44±0.08| 0.3F    | 1    | 41.80±0.12      |
| 16  | 79     | 2.05            | 0.30±0.05| 0.00±0.17| 1 | 41.68±0.06      |
| 17  | 362    | 7.57            | 1.0F     | 0.3F    | U    | <42.78          |
| 20  | 290    | 9.64            | 1.0F     | 0.3F    | U    | <42.63          |
| 21  | 151    | 2.60            | 1.0F     | 0.3F    | U    | <42.33          |
| 22  | 54     | 3.80            | 1.0F     | 0.3F    | U    | <41.15          |
| 23  | 97     | 5.91            | 1.0F     | 0.3F    | U    | <41.72          |
| 24  | 183    | 5.30            | 1.0F     | 0.3F    | U    | <42.52          |
| 26  | 189    | 4.73            | 1.0F     | 0.3F    | U    | <41.95          |
| 27  | 524    | 4.10            | 1.0F     | 0.3F    | U    | <43.03          |
| 28  | 228    | 5.55            | 1.0F     | 0.3F    | U    | <42.70          |
| 29  | 628    | 2.50            | 1.0F     | 0.3F    | U    | <43.02          |
| 30  | 92     | 4.65            | 1.0F     | 0.3F    | U    | <42.07          |
| 31  | 82     | 4.71            | 1.0F     | 0.3F    | U    | <41.93          |
| 32  | 245    | 5.87            | 1.0F     | 0.3F    | U    | <42.51          |
| 33  | 156    | 18.50           | 0.61±0.30| 0.3F    | 1    | 41.77±0.11      |
| 34  | 184    | 16.42           | 1.0F     | 0.3F    | U    | <42.55          |
| 35  | 325    | 2.54            | 0.91±0.18| 0.16±0.23| 2 | 42.35±0.11      |
| 37  | 134    | 1.93            | 0.67±0.11| 0.17±0.15| 1 | 42.12±0.06      |
| 38  | 175    | 3.02            | 1.0F     | 0.3F    | U    | <42.01          |
| 39  | 420    | 3.23            | 1.0F     | 0.3F    | U    | <42.80          |
| 40  | 134    | 3.15            | 1.0F     | 0.3F    | U    | <41.73          |
| 42  | 80     | 3.94            | 0.82±0.03| 0.50±0.24| 1 | 42.16±0.02      |
| 43  | 198    | 3.30            | 1.0F     | 0.3F    | U    | <42.40          |
| 44  | 28     | 1.98            | 1.0F     | 0.3F    | U    | <40.84          |
| 45  | 439    | 0.81            | 1.0F     | 0.3F    | U    | <42.60          |
| 46  | 162    | 2.94            | 1.0F     | 0.3F    | U    | <42.25          |
| 47  | 190    | 3.79            | 1.0F     | 0.3F    | U    | <42.33          |
| 48  | 56     | 4.53            | 1.09±0.21| 0.69±0.10| 2 | 41.58±0.14      |
| 49  | 199    | 1.64            | 1.0F     | 0.3F    | U    | <42.26          |
| 50  | 835    | 0.78            | 1.0F     | 0.3F    | U    | <42.40          |
Table 2. continued

| HCG | $d$ (Mpc) | $N_H$ ($10^{20}$cm$^{-2}$) | $T$ (keV) | $Z$ (solar) | Qual | log $L_X$ (erg s$^{-1}$) |
|-----|-----------|-------------------|--------|-------|-----|-------------------|
| 51  | 155       | 1.21              | 1.0F   | 0.3F  | 2   | 42.99±0.11        |
| 52  | 258       | 1.58              | 1.0F   | 0.3F  | U   | <42.50            |
| 53  | 124       | 1.70              | 1.0F   | 0.3F  | U   | <42.17            |
| 55  | 315       | 1.51              | 1.0F   | 0.3F  | U   | <42.45            |
| 56  | 162       | 1.11              | 1.0F   | 0.3F  | U   | <42.23            |
| 57  | 182       | 1.70              | 0.82±0.27 | 0.48±0.88 | 1 | 41.98±0.21        |
| 58  | 124       | 3.10              | 0.64±0.19 | 0.0±0.16 | 1 | 41.89±0.11        |
| 59  | 81        | 2.94              | 1.0F   | 0.3F  | U   | <42.00            |
| 61  | 78        | 1.68              | 1.0F   | 0.3F  | U   | <41.91            |
| 62  | 82        | 3.00              | 0.96±0.04 | 0.15±0.06 | 1 | 43.04±0.03        |
| 63  | 186       | 5.82              | 1.0F   | 0.3F  | U   | <42.49            |
| 64  | 216       | 2.41              | 1.0F   | 0.3F  | U   | <42.48            |
| 66  | 419       | 1.24              | 1.0F   | 0.3F  | U   | <42.67            |
| 67  | 145       | 2.16              | 0.82±0.19 | 0.49±0.53 | 1 | 41.69±0.10        |
| 68  | 48        | 0.90              | 0.54±0.15 | 0.43±0.98 | 1 | 41.27±0.26        |
| 69  | 176       | 1.44              | 1.0F   | 0.3F  | U   | <42.33            |
| 70  | 381       | 1.24              | 1.0F   | 0.3F  | U   | <42.63            |
| 71  | 180       | 1.53              | 1.0F   | 0.3F  | U   | <42.28            |
| 72  | 252       | 2.34              | 1.0F   | 0.3F  | U   | <42.54            |
| 73  | 269       | 3.06              | 0.59†   | 0.0†  | 2   | 42.43±0.24        |
| 74  | 239       | 4.01              | 1.0F   | 0.3F  | U   | <42.67            |
| 75  | 249       | 4.15              | 1.0F   | 0.3F  | U   | <42.72            |
| 76  | 204       | 3.82              | 1.0F   | 0.3F  | U   | <42.66            |
| 79  | 87        | 3.51              | 1.0F   | 0.3F  | U   | <41.71            |
| 80  | 186       | 2.42              | 1.0F   | 0.3F  | U   | <42.16            |
| 81  | 299       | 4.41              | 1.0F   | 0.3F  | U   | <42.60            |
| 82  | 217       | 1.74              | 1.0F   | 0.3F  | U   | <42.29±0.14       |
| 83  | 318       | 5.86              | 1.0F   | 0.3F  | 2   | 42.81±0.12        |
| 84  | 333       | 3.61              | 1.0F   | 0.3F  | U   | <41.92            |
| 85  | 236       | 6.58              | 1.0F   | 0.3F  | U   | <42.70±0.10       |
| 86  | 119       | 8.56              | 1.0F   | 0.3F  | 2   | 42.32±0.14        |
| 87  | 177       | 5.12              | 1.0F   | 0.3F  | U   | <42.36            |
| 88  | 121       | 4.60              | 1.0F   | 0.3F  | U   | <42.18            |
| 89  | 178       | 4.64              | 1.0F   | 0.3F  | U   | <42.30            |
| 90  | 53        | 1.50              | 0.68±0.12 | 0.20±0.16 | 1 | 41.48±0.09        |
| 92  | 129       | 6.70              | 0.75±0.08 | 0.23±0.51 | 1 | 42.16±0.04        |
| 93  | 101       | 4.70              | 1.0F   | 0.3F  | U   | <41.34            |
| 95  | 237       | 4.38              | 1.0F   | 0.3F  | U   | <42.43            |
| 96  | 175       | 4.61              | 1.0F   | 0.3F  | U   | <42.11            |
| 97  | 131       | 3.29              | 0.87±0.05 | 0.12±0.04 | 1 | 42.78±0.02        |
| 98  | 159       | 2.81              | 1.0F   | 0.3F  | U   | <42.27            |
| 99  | 174       | 4.87              | 1.0F   | 0.3F  | U   | <42.34            |
| 100 | 107       | 4.30              | 1.0F   | 0.3F  | U   | <41.99            |
Table 3. Cluster data used in Figs.8, 12 and 13, taken from Edge & Stewart (1991) and Yamashita (1992).

| Cluster   | $z$      | log$\sigma$ (km s$^{-1}$) | $T$ (keV) | log$L_X$ (erg s$^{-1}$) |
|-----------|----------|----------------------------|-----------|--------------------------|
| Perseus   | 0.0184   | 3.106                      | 6.08±0.20 | 45.362±0.019             |
| A478      | 0.0882   | 2.956                      | 6.70±0.19 | 45.683±0.015             |
| A496      | 0.0320   | 2.848                      | 3.91±0.06 | 44.826±0.071             |
| A1060     | 0.0114   | 2.784                      | 2.55±0.04 | 43.820±0.046             |
| A1367     | 0.0215   | 2.915                      | 3.50±0.18 | 44.246±0.047             |
| Virgo     | 0.0038   | 2.758                      | 2.34±0.02 | 43.568±0.071             |
| Centaurus | 0.0109   | 2.768                      | 3.54±0.13 | 44.167±0.038             |
| Coma      | 0.0232   | 3.004                      | 8.11±0.07 | 45.204±0.027             |
| A1795     | 0.0621   | 2.888                      | 5.34±0.11 | 45.292±0.027             |
| A2142     | 0.0899   | 3.094                      | 8.68±0.20 | 45.777±0.023             |
FIGURE CAPTIONS

Figure 1: Radial profile of diffuse X-ray emission from HCG16, with flux from the member galaxies excised.

Figure 2: Contours of X-ray surface brightness (0.1-2.4 keV) after smoothing with an adaptive filter, superimposed on an optical image of the group. The dashed circle has a radius of 200 kpc.

Figure 3: PSPC spectrum of the diffuse emission from HCG16, with best fitting ($T = 0.3 \text{ keV}$, $Z = 0$) hot plasma model overlaid.
Figure 4: Bolometric X-ray luminosities and $3\sigma$ upper limits plotted against redshift for the 85 survey groups.

Figure 5: X-ray and blue luminosities for the 22 detected HCGs. Groups with dominant early type galaxies are plotted as ellipses, whilst those with dominant spirals are shown as crosses. Systems in which the galaxies are not resolved from the diffuse emission (i.e. with quality flag $q = 2$) are shown dotted. Vertical extent represents $1\sigma$ error in $L_X$, but horizontal extent is arbitrary.

Figure 6: Distribution of X-ray/optical luminosity ratio for the detected systems.

Figure 7: Distribution of derived plasma temperature for HCGs with adequate statistics to allow a fit.

Figure 8: $L_X : T$ relation for HCGs (crosses) and a sample of clusters (diamonds) – $q = 1$ (i.e. fully resolved) systems are shown as barred crosses. Vertical and horizontal extent represent $1\sigma$ errors. The solid and dotted lines overlaid on the groups indicate the best fit regression line and its $1\sigma$ envelope. The bold solid line is a fit to the whole group + cluster sample, whilst the dashed line labelled CL shows the relation derived for a large cluster sample by White et al. (in preparation).

Figure 9: Luminosity distribution for HCGs dominated by (a) early and (b) late type galaxies. The distribution for the full sample is overlaid as a dotted line.

Figure 10: Relationship between spiral fraction and (a) X-ray luminosity, and (b) temperature. Barred crosses denote high quality ($q = 1$) groups. Values of the K statistic for the full sample and the $q = 1$ systems only (in brackets) are given.
Figure 11: $L_X : \sigma$ plot, including $3\sigma$ upper limits, for the full HCG sample. High quality ($q = 1$) groups are plotted as barred crosses. Errors bars correspond to $1\sigma$. Values of the K statistic for the full detected subsample and the $q = 1$ systems only (in brackets) are given.

Figure 12: $L_X : \sigma$ relation for HCGs (crosses) and clusters (diamonds). Vertical and horizontal extent represent $1\sigma$ errors. $q = 1$ groups are shown as barred crosses. The solid and dotted lines overlaid on the groups indicate the best fit regression line and its $1\sigma$ envelope. The bold solid line is a fit to the whole group + cluster sample, whilst the dashed line labelled CL shows the relation derived for a large cluster sample by White et al. (in preparation).

Figure 13: $\sigma : T$ relation for HCGs (crosses) and clusters (diamonds). Vertical and horizontal extent represent $1\sigma$ errors. $q = 1$ groups are shown as barred crosses. The solid and dotted lines overlaid on the groups indicate the best fit regression line and its $1\sigma$ envelope. The bold solid line is a fit to the whole group + cluster sample, and the dotted line is the locus along which $\beta = 1$, i.e. specific energy in gas and galaxies is equal.

Figure 14: Distribution of metallicity for HCGs in which it was possible to fit for it.

Figure 15: (a) Estimated frequency distribution of bolometric X-ray luminosity for the sample of 62 systems with $z < 0.04$ (see text for details), and (b) the corresponding cumulative distribution.

Figure 16: Normalised luminosity function for HCGs with $z < 0.04$ and $\geq 4$ accordant galaxies. The dashed line is the best power law fit to these points (excluding the lowest bin, which is probably underestimated). Also shown are the cluster XLF of Ebeling et al. 1996 (solid line), and the $1\sigma$ error envelope for the power law XLF of Henry et al. 1992 (dotted), as well as the loose group space density derived by Henry et al. 1995. Vertical error bars are $1\sigma$. 
This figure "hcgfig2.gif" is available in "gif" format from:

http://arxiv.org/ps/astro-ph/9607114v1
