AN X-RAY SURVEY OF GALAXIES IN PAIRS

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ABSTRACT

Results are reported from the first survey of X-ray emission from galaxies in pairs. The sample consists of 52 pairs of galaxies from the Catalog of Paired Galaxies whose coordinates overlap the ROSAT Position Sensitive Proportional Counter pointed observations. The mean observed log $L_X$ for early-type pairs is $41.35 \pm 0.21$, while the mean log $L_X$ predicted using the $L_X-L_B$ relationship for isolated early-type galaxies is $42.10 \pm 0.19$. With 95% confidence, the galaxies in pairs are underluminous in the X-ray, compared with isolated galaxies, for the same $L_B$. A significant fraction of the mixed pair sample also appears similarly underluminous. A spatial analysis shows that the X-ray emission from pairs of both types typically has an extent of $\sim 10\text{--}50$ kpc, much smaller than the group intergalactic medium, and thus likely originates from the galaxies. CPG 564, the most X-ray luminous early-type pair, $4.7 \times 10^{42}$ ergs s$^{-1}$, is an exception. The extent of its X-ray emission, greater than 169 kpc, and HWHM, $\sim 80$ kpc, is comparable to that expected from an intergalactic medium. The sample shows only a weak correlation, $\sim 81\%$ confidence, between $L_X$ and $L_B$, presumably due to variations in gas content within the galaxies. No correlation between $L_X$ and the pair velocity difference ($\Delta v$), separation ($\Delta r$), or far-infrared luminosity ($L_{FIR}$) is found, although the detection rate is low, 22%.

Subject heading: galaxies: clusters: general — galaxies: interactions — surveys — X-rays: galaxies

1. INTRODUCTION

Studies of paired galaxies in the radio, infrared, and optical provide important details regarding the role of interactions and mergers in the evolution of galaxies. Evidence of interaction is inferred from excess emission in the far-infrared (FIR) and optical relative to isolated galaxies, which indicates an increased level of star formation from the interaction (Bushouse 1987). While these data provide a description of the star formation history of the galaxies, X-ray studies address the fate of gas heated by the large energy input from stellar evolution, such as the formation of a superwind (Heckman, Armus, & Miley 1990). Comparisons of the X-ray and optical luminosity of paired with isolated galaxies provides important details of the connection between star formation and hot gas. Studies of the hot, X-ray-emitting gas content of interacting galaxies also has important implications for the enrichment of the intracluster and intergalactic medium. Recent studies of cluster abundances indicate that the enrichment of the intracluster medium (ICM) has changed little since $z \sim 0.3$, suggesting that enrichment must have occurred in protogalaxies rather than during cluster evolution (Mushotzky & Loewenstein 1997). Although local systems are studied here, the results pertaining to the fate of hot gas in paired, interacting galaxies could be applied equally well to protogalactic pairs within clusters.

The X-ray observations are also in a unique position to address the connection between pairs and groups of galaxies. Groups typically have a hot intergalactic medium. If mixed- and early-type pair morphologies were merger remnants of groups, then they would retain the hot intergalactic medium of the group, being characterized by an extended X-ray component greater than 200 kpc, as is typical of groups (Mulchaey et al. 1996). In addition, the total X-ray luminosity of compact groups is higher than that expected from the galaxies themselves (Ponman & Bournier 1997). Detection of the fossil intergalactic medium would make a strong argument that mergers take place within groups.

In this paper, we present the characteristics of the sample and details on the data analysis in $\S$ 2. In $\S$ 3 we present the results of correlation tests on the entire sample ($\S$ 3.1) and comparisons of the X-ray emission of paired versus isolated galaxies for spiral pairs ($\S$ 3.2), early-type pairs ($\S$ 3.3), and mixed pairs ($\S$ 3.4). In $\S$ 4 results of the spatial analysis are presented. In $\S$ 5 the results are summarized. A value of 50 km s$^{-1}$ Mpc$^{-1}$ is used for all calculated quantities.

2. DATA ANALYSIS

We have checked the ROSAT Position Sensitive Proportional Counter (PSPC) pointed data archives for serendipitous occurrences of over 600 pairs of galaxies from the optically selected Catalog of Paired Galaxies (CPG) by Karachentsev (1972). Fifty-eight pair positions overlap PSPC pointings. The PSPC is the best instrument to use for this survey because of its larger field of view and greater sensitivity when compared with other available instruments such as the ROSAT high-resolution imager or the Einstein imaging proportional counter (IPC). The pointed observations, while not providing all-sky coverage, have the advantage of much longer exposure times than those of the ROSAT all-sky survey (RASS), $\sim 550$ s, which is necessary since most of these sources are below the flux limit of the RASS, $\sim 4 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$. Using ROSAT for a survey of optically selected groups, Mahdavi et al. (1997) found that only seven out of 32 objects are detected on RASS fields, of which three are intrinsically much brighter Abell clusters. We detect 11 out of 49 pairs, excluding active galactic nuclei (AGNs), at greater than 3 $\sigma$. The range in X-ray luminosity of groups in their survey exceeds more than 50% of the pairs so that our higher detection rate must be attributed to the longer pointed observations. For a velocity of 6000 km s$^{-1}$, typical of the paired galaxies, the minimum measurable luminosity with RASS would be $\sim 3 \times 10^{41}$ ergs s$^{-1}$. Thus, using the correlations found in this paper, we could expect to detect only the X-ray brightest pairs, typically those containing Seyfert galaxies, which
are not suitable for study of the hot gas content.

We excluded pairs that have a high velocity difference and are therefore chance alignments: CPG 391 (greater than 4000 km s⁻¹), CPG 321 (greater than 500 km s⁻¹), and CPG 166 (greater than 2000 km s⁻¹). Pairs in galaxy clusters were also eliminated since they are contaminated by the intracluster medium: CPG 588 (in A2634), CPG 464 (in A2063), and CPG 361 (in Coma). CPG 353 is in the outskirts of the Virgo cluster where the contribution from the intracluster medium is negligible, and it is included in the sample. The best-fit temperature for CPG 353 is 0.82 keV, more typical of emission associated with a galaxy than a

| CPG  (1) | Type (2) | R.A. (3) | Decl. (4) | Separation (arcmin) (5) | Velocity (km s⁻¹) (6) | Lₓ (10⁴⁴ ergs s⁻¹) (7) | σ (counts s⁻¹) (8) | Lₓ (10⁴⁴ ergs s⁻¹) (9) | log Lₓ,corr (10) |
|---|---|---|---|---|---|---|---|---|---|

Table 1: Data for Spiral Galaxy Pairs

Note: Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
cluster. Since we are addressing the nature of the hot gas content in galaxy pairs, those with AGNs were eliminated: CPG 510, CPG 419, and CPG 238. CPG 234 also has an extended component (2.3 or 40 kpc in extent) as well as an AGN (CPG 510, CPG 419, and CPG 238. CPG 234 also has an AGN associated with the galaxies themselves including plumes (Dahlem et al. 1996) to analyze the source regions using routines that are part of the imaging and spectral analysis package in PROS version 2.4 (Deponte et al. 1995).

Signal-to-noise ratios (S/Ns) are given in Table 4. The detection threshold is 3 σ or higher significance. For those source regions with count rates below the detection threshold, an upper limit is calculated equal to 3 σ. Spectra for all detected objects were modeled using XSPEC version 9.0 (Arnaud 1996) to obtain the flux. The model consists of a Raymond & Smith (1997) plasma code with absorption cross sections (Morrison & McCammon 1983) using galactic column densities at the source positions (Stark 1992) (values given in Table 4) and solar abundance ratios (Anders & Grevesse 1989). The data were grouped to contain at least 20 counts in each bin to increase the reliability of the results obtained from a χ^2 fit (Nousek & Shue 1989). The best-fit plasma temperatures and 90% confidence range from the spectral analysis are given in Table 5.

Upper limits are converted to fluxes using a Raymond & Smith model convolved with the PSPC response matrix assuming solar abundance and a temperature of 1 keV for early-type and mixed pairs (Kim, Fabbiano, & Trinchieri 1989). The best-ﬁt plasma temperatures and 90% confidence range from the spectral analysis are given in Table 5.

Four of the detected pairs were ROSAT targets: 125, 218, 278, and 353. Two are spiral pairs and two are mixed-type pairs (CPG 278 and CPG 353). Therefore, the collection of eight early-type pairs contains only serendipitous observations and represents the unbiased X-ray characteristics of the sample.

Each galaxy pair was first located on the Digitized Sky Survey (DSS) to check the accuracy of the CPG positions. The right ascension and declination given in Tables 1, 2, and 3 have been modified for some pairs to reflect more accurate coordinates obtained from the DSS than in the CPG. The region size of the image used to measure the X-ray emission was chosen with consideration of the nominal extent of possible extended X-ray emission associated with the galaxies themselves including plumes (Dahlem et al. 1996; Fabbiano 1988), halos (Trinchieri & Fabbiano 1985; Forman, Jones, & Tucker 1985), or the nominal core radius of intergalactic emission from a fossil group using NGC 2300 as a prototype (Davis et al. 1996). It is important to use a fixed, distance-independent–region for all pairs. This region is a circle with radius equal to the pair separation (in kpc) plus twice the nominal galaxy radius, ~50 kpc. In most cases, the emission from either galaxy and from an intergalactic medium would be included within this region. Contaminating point sources were removed when necessary. For wider pair separations or especially difficult locations on the image, a circular region of radius 50 kpc centered on the coordinates of the optically brightest galaxy was used. The size and location of each source region is given in Table 4. Standard PSPC analysis procedures for extended sources, including background subtraction, vignetting and exposure map corrections (Table 4), and charged particle elimination, were followed as outlined in Snowden et al. (1994) to analyze the source regions using routines that are part of the imaging and spectral analysis package in PROS version 2.4 (Deponte et al. 1995).

TABLE 2

| CPG (1) | Type (2) | R.A. (3) | Decl. (4) | Separation (arcmin) (5) | Velocity (6) | $L_x$ (10$^{43}$ ergs s$^{-1}$) (7) | counts s$^{-1}$ $\times 10^{-2}$ (8) | $\sigma$ (counts s$^{-1}$) (9) | $L_x$ (10$^{44}$ ergs s$^{-1}$) (10) |
|--------|---------|---------|----------|--------------------------|-------------|---------------------------------|---------------------------------|-----------------|---------------------------------|
| 18.....| E       | 00 48 31| 01 21 17 | 0.34                     | 18648       | 36.30                           | 0.82                            | 0.34            | <14.9                           |
| 90.....| E       | 00 48 30| 01 21 12 | ...                      | 19003       | 54.40                           | ...                             | ...             | ...                             |
| 99.....| E       | 03 25 04| 02 53 46 | 1.07                     | 9487        | 7.73                            | 0.18                            | 0.16            | <1.65                           |
| 320....| E       | 12 05 41| 01 35 37 | 1.10                     | 5959        | 5.45                            | 0.064                           | 0.24            | <0.98                           |
| 367.....| S0?     | 13 14 52| 17 13 36 | 1.28                     | 7087        | 9.62                            | ~0.80                           | 2.73            | <16.60                          |
| 564.....| SA0-    | 22 14 47| 13 50 25 | 0.59                     | 8212        | 11.70                           | 6.07                            | 0.76            | 46.5                            |
| 574.....| S0      | 22 51 00| 31 22 28 | 0.57                     | 6778        | 14.5                            | 0.48                            | 1.32            | <7.87                           |

**Note:** Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
### Table 3

**Data for Mixed Galaxy Pairs**

| CPG (1) | Type (2) | R.A. (3) | Decl. (4) | Separation (arcmin) (5) | Velocity (km s\(^{-1}\)) (6) | \(L_x\) (10\(^{44}\) ergs s\(^{-1}\)) counts s\(^{-1}\) \(\times\) 10\(^{-2}\) (7) | \(\sigma\) (counts s\(^{-1}\)) (8) | \(L_x\) (10\(^{44}\) ergs s\(^{-1}\)) log \(L_{\text{FIR}}\) (10) | Note |
|--------|----------|---------|----------|-------------------------|-----------------------------|-------------------------------|-----------------------------|--------------------------------|------|
| 83 ...... Ring A | 02 55 10 | -00 10 41 | 0.71 | 8514 | 37.20 | 0.17 | 0.26 | <2.33 | 45.04 |
| 84 ...... Ring B | 02 55 12 | 00 11 00 | ... | 8714 | 23.90 | ... | ... | ... | ... |
| 116 ...... Sc | 07 02 31 | 86 34 47 | 1.57 | 5005 | 2.00 | 0.22 | 0.34 | <1.04 | 43.75 |
| 144 ...... E | 07 48 13 | 28 13 30 | 0.54 | 8107 | 9.99 | 0.64 | 0.54 | <4.36 | ... |
| 234 ...... E2 | 10 23 27 | 19 53 50 | 2.35 | 1168 | 2.09 | ... | ... | ... | 44.66 |
| 238 ...... E | 10 34 30 | 39 36 54 | 2.34 | 12862 | 13.70 | 331.70 | 3.17 | 867. ... | 43.39 |
| 239 ...... E? | 10 36 21 | 58 37 11 | 3.92 | 8216 | 15.30 | 1.82 | 0.92 | <7.65 | ... |
| 243 ...... S0 | 10 40 45 | 39 04 25 | 1.08 | 9015 | 3.66 | 0.19 | 0.19 | <1.91 | ... |
| 260 ...... E? | 10 59 59 | 50 03 24 | 2.72 | 7235 | 9.66 | 0.44 | 0.39 | <2.54 | ... |
| 278 ...... SA(s) | 11 16 55 | 18 03 04 | 5.96 | 841 | 7.44 | 8.52 | 0.71 | 0.45 | ... |
| 339 ...... SB0? | 12 28 13 | 13 53 56 | 1.57 | 7041 | 8.42 | 1.94 | 0.71 | <4.44 | ... |
| 345 ...... S0/a | 12 32 48 | 63 56 22 | 4.02 | 2591 | 5.46 | 0.055 | 0.32 | <0.32 | ... |
| 353 ...... SB(dm) | 12 32 34 | 63 52 38 | ... | 3073 | 2.02 | ... | ... | ... | 43.00 |
| 402 ...... S0 | 13 55 59 | 17 29 57 | 0.73 | 6202 | 2.10 | 0.40 | 0.22 | <1.11 | ... |
| 494 ...... E | 16 17 36 | 46 04 57 | 1.15 | 6102 | 2.25 | -0.68 | 1.13 | <5.00 | ... |
| 508 ...... E0 | 17 19 14 | 48 58 50 | 3.79 | 7488 | 5.69 | 0.65 | 0.32 | <2.14 | ... |
| 510 ...... E | 17 19 21 | 49 02 50 | ... | 7420 | 8.30 | ... | ... | ... | 43.92 |
| 530 ...... E | 18 10 58 | 31 06 56 | 9.27 | 7227 | 14.50 | -0.50 | 0.72 | <4.60 | ... |
| 548 ...... E+pec | 20 47 24 | 00 18 02 | 1.76 | 4032 | 5.99 | 0.95 | 0.47 | <1.03 | ... |

**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

galaxy classification from NASA/IPAC Extragalactic Database (NED), columns (3) and (4) are the R.A. and decl. in J2000 coordinates, column (5) is the separation of galaxies in minutes of arc, column (6) is the galaxy recessional velocity in \(\text{km s}^{-1}\), column (7) is the blue luminosity in units of \(10^{43} \text{ergs s}^{-1}\), column (8) is the background-subtracted X-ray count rate in counts \(\text{s}^{-1}\), column (9) is the \(\sigma\) error in counts \(\text{s}^{-1}\), column (10) is the X-ray luminosity in the 0.25–2 keV band in units of \(10^{44} \text{ergs s}^{-1}\), and column (11) is \(L_{\text{FIR}}\). Data in columns (1) and (3)–(7) are based on information from Karachentsev (1972). A Hubble constant of 50 \(\text{km s}^{-1}\ \text{Mpc}^{-1}\) is used to calculate the luminosities. Column (11) is calculated from fluxes obtained from the Catalogue of Galaxies and Quasars Observed in the IRAS Survey, version 2.1, as well as the Point Source Catalog and the Faint Source Catalog. The FIR sources occur within a 25 kpc search radius centered on each of the galaxy positions.

Table 4 contains information supplemental to that in Tables 1–3. The contents of the tables are the following: column (1) is the pair number in the CPG, column (2) is the PSPC sequence number, column (3) is the size of the source region in arcminutes, column (4) is the distance of the analyzed region from the center of the image in arcminutes, column (5) is the exposure time, column (6) is the signal-to-noise/3, column (7) is the exposure map correction, which includes vignetting and correction for the instrument supports, column (8) is the hydrogen column density, and column (9) gives galaxy UGC, NGC, IC, and CGCG designations of the galaxies in Tables 1–3.

### 3. RESULTS

#### 3.1. Correlations

Normal galaxies all show a correlation between the optical and X-ray luminosity. These correlations allow linking the stellar sources to the amount of hot gas, both stellar and diffuse, thus providing clues to the origin of the X-ray emission. Correlation tests were performed on the subsample of pairs, which included all galaxy types, using \(L_{\text{X}}\) as the dependent variable and the physical quantities \(L_{\text{opt}}\), \(L_{\text{IR}}\), \(\sigma\), and \(\Delta v\) as independent variables.

The \(L_{\text{X}}-L_{\text{opt}} \) correlation and other correlation tests were performed using ASURV Rev. 1.2 (LaValley, Isobe, & Feigelson 1992), which implements the methods described by...
| CPG (1) | PSPC (2) | Radius of Circle (arcmin) | Angle from Center of Image (arcmin) | Exposure Time (s) | (S/N)/3 (counts s$^{-1}$) | Exposure Map Correction (7) | Column Density (10$^4$ cm$^{-2}$) | Common Galaxy Names (9)* |
|---------|----------|---------------------------|-----------------------------------|------------------|----------------------------|-----------------------------|-------------------------------|---------------------------|
| 3 ........ rp200645 | 3.5 | 510 | 2717 | 0.32 | 1.67 | 4.7 | N27, U96, C00079 + 2844; U95, C00079 + 2843 |
| 7 ........ rp201070s00 | 4.4 | 470 | 4849 | 0.10 | 1.77 | 5.8 | C0018.6 + 3011; C0018.7 + 3014 |
| 13 ........ rp300446a00 | 3.8 | 33 | 7709 | 0.19 | 1.04 | 3.3 | N169, U365, C0034.2 + 2343; N169A, C0034.2 + 2343 |
| 18 ........ rp700377a00 | 2.9 | 38.13 | 10447 | 0.79 | 1.41 | 2.6 | U1559, U496, C00459 + 0105; U496, C00459 + 0105 |
| 31 ........ rp701047a00 | 4.0 | 0.50 | 13894 | 0.75 | 1.03 | 2.9 | N520, U966, C01221 + 033; N520, U966, C01221 + 033 |
| 83 ........ rp701036a00 | 2.3 | 21.87 | 11863 | 0.22 | 1.65 | 3.5 | N1143, U1288, C0252.6 - 0023; N1144, U1288, C0252.6 - 0023 |
| 90 ........ rp700999 | 3.0 | 33.79 | 25727 | 0.39 | 1.71 | 8.8 | C0122.4 + 023; C0122.4 + 024 |
| 99 ........ rp700417e00 | 3.3 | 15.28 | 10640 | 1.16 | 1.17 | 0.5 | N1587, U3063, C0428.1 + 0033; N1588, U3064, C0428.2 + 0033 |
| 116 ........ rp900312a00 | 3.6 | 55.20 | 9627 | 0.24 | 2.21 | 6.6 | U03 024A, C03620 + 8600; U3576A, C0365.0 + 8386 |
| 125 ........ wp700470e00 | 3.4 | 146 | 9982 | 1.74 | 1.03 | 5.4 | N2341, U7308, C0706.3 + 2040; N2342, U7308, C0706.4 + 2043 |
| 136 ........ wp500113 | 2.6 | 31.13 | 4487 | 0.44 | 1.38 | 6.9 | C0724.2 + 1944; C0724.5 + 1943 |
| 137 ........ rp600230a00 | 3.3 | 24.10 | 8782 | 1.40 | 1.89 | 3.6 | U3906, C0730.4 + 7434; U3906, C0730.4 + 7437 |
| 140 ........ rp200896 | 3.0 | 24.71 | 8046 | 0.38 | 1.48 | 4.7 | U3995, C0741.0 + 2921; U3995, C0741.0 + 2921 |
| 144 ........ wp200175 | 3.4 | 40.33 | 8837 | 0.40 | 1.48 | 3.4 | U4300, C0745.1 + 2820; U4300, C0745.1 + 2820 |
| 161 ........ rp600542a00 | 2.8 | 44.29 | 2714 | 0.39 | 1.78 | 4.3 | C1238, U4383, C0820.7 + 2130; C1239, U4383, C0820.7 + 2130 |
| 163 ........ rp701976a00 | 2.9 | 43.54 | 1713 | 0.74 | 1.77 | 4.5 | C0825.2 + 5540; U4472, C0825.3 + 5540 |
| 171 ........ rp300203a00 | 3.3 | 23.29 | 4908 | 0.24 | 1.85 | 3.8 | C0843.3 + 1259; C0843.1 + 1258 |
| 175 ........ rp700541 | 3.8 | 39.39 | 6062 | 1.07 | 1.58 | 0.24 | N2672, U4619, C0846.5 + 1916; N2673, U4620, C0846.5 + 1916 |
| 186 ........ rp800602a00 | 3.5 | 12.97 | 7535 | 0.45 | 1.09 | 3.5 | N2750, U4769, C0902.8 + 2538; N2750, U4769, C0902.8 + 2538 |
| 200 ........ rp900466a00 | 3.6 | 33.74 | 6624 | 1.31 | 1.42 | 3.6 | C0921.0 + 6447; C0921.1 + 6445 |
| 218 ........ wp300382e00 | 39.0 | 53.00 | 28350 | 13.07 | 20.3 | 0.24 | M82, N2024, U5322, C0917.1 + 6955; M81, N3031, U5318, C0914.9 + 6918 |
| 234 ........ rp200076 | 10.8 | 53.00 | 26522 | 19.30 | 27.3 | 0.18 | N3226, U5617, C1020.7 + 2008; N3227, U5620, C1020.9 + 2006 |

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* Common galaxy names: (N)GC, (U)GC, (I)C, (C)GCG.
Table 5

X-RAY SPECTRAL RESULTS

| CPG   | Number of Bins | $\chi^2$ | Best-fit Temperature (keV) | 90% Confidence Range (keV)* |
|-------|----------------|---------|--------------------------|-----------------------------|
| 99    | 6              | 0.36    | 0.99                     | 0.44–64                     |
| 125   | 11             | 0.16    | 1.09                     | 0.37–64                     |
| 137   | 6              | 0.37    | 0.83                     | 0.06–47.0                   |
| 175   | 6              | 0.04    | 0.68                     | 0.27–64                     |
| 218   | 151            | 0.48    | 0.85                     | 0.70–1.14                   |
| 234   | 162            | 0.85    | 2.09                     | 1.67–2.73                   |
| 278   | 84             | 33.9    | 0.40                     | 0.31–0.57                   |
| 347   | 10             | 0.33    | 1.71                     | 0.31–64                     |
| 353   | 117            | 0.60    | 0.82                     | 0.78–0.85                   |
| 378   | 8              | 0.11    | 1.07                     | 0.10–64                     |
| 564   | 20             | 0.34    | 1.03                     | 0.77–1.93                   |

* Value of 64 keV is the hard limit imposed by the spectral fitting routine.

Table 6

CORRELATION TEST RESULTS: ALL PAIRS

| DV               | IV | DET/TOT | GKT | Slope | Error | IC | Error |
|------------------|----|---------|-----|-------|-------|----|-------|
| $\log (l_X)$ (0.25–2 keV) | 11/49 | 0.81 | 0.25 | 0.49 | 29.78 | ... |
| $\log (l_X)$     | 7/36 | 0.40 | ...  | ...  | ...   | ... |
| $\log (l_B)$     | 11/49 | 0.69 | -0.51 | 0.65 | 40.20 | ... |
| $\log (\Delta v)$ | 11/49 | 0.52 | ...  | ...  | ...   | ... |

Table 7

MEAN VALUES OF SAMPLE QUANTITIES

| Sample                  | Quantity | Mean    | Error |
|-------------------------|----------|---------|-------|
| Spiral pairs            | $\log (l_X)$ | 40.82   | 0.11  |
| Normal spirals          | $\log (l_X)$ | 39.87   | 0.11  |
| Early-type pairs        | $\log (l_X)$ | 41.35   | 0.21  |
| Normal early-type       | $\log (l_X)$ | 42.00   | 0.13  |
| Mixed pairs             | $\log (\text{obs. } l_X)$ | 40.87   | 0.11  |
| All pairs               | $\log (l_X)$ | 40.86   | 0.09  |
| Compact groups          | $\log (l_X)$ | 41.59   | 0.11  |

* ROSAT PSPC data: extrapolated to 0.5–3 keV.
$b$ Einstein IPC data: 0.5–3 keV.
$c$ ROSAT PSPC data: 0.2–4 keV.
$E$ Einstein IPC data: 0.2–4 keV.
$K$ ROSAT PSPC data: 0.25–2 keV.

With a mean value of $\sim 10^{44}$ ergs s$^{-1}$, the range in $\log (l_X)$ is much larger, a factor of $\sim 10^4$, and the mean is lower, 40.86 (see Table 7). There is a general linear trend between $\log (l_X)$ and $\log (l_B)$. However, the scatter is significant at all luminosities and increases at higher $l_B$. This figure also shows that the $l_X$-$l_B$ locus is very different for each pair type. Even though there is a weak correlation present, 81%, it is not very tight as is apparent in the large error in the slope.

Strong FIR emission is an indicator of active star formation since interacting galaxies show a high $l_{\text{FIR}}/l_B$. Close pairs of galaxies with spirals are generally stronger FIR emitters (Xu & Sulentic 1991) implying that they are interacting and should be emitting X-rays associated with massive stars, X-ray binaries, and interstellar gas heated by Type II supernovae. Thirty-six of the spiral pairs and mixed pairs were detected in the FIR, but none of the early-type pairs were detected. Figure 2 shows $l_{\text{FIR}}$ and $l_X$. The quantity $l_{\text{FIR}}$, is calculated from the cataloged FIR flux: $\log F_{\text{FIR}} = \log [1.26 \times (F_{60} + F_{100})]$, where $F_{60} = 2.58 \times 10^{-14} \times F_{\text{FIR}}(60 \ \mu m)$ and $F_{100} = 1.00 \times 10^{-14} \times F_{\text{FIR}}(100 \ \mu m)$. The fluxes at 60 and 100 $\mu m$ are in Janskys.
Fig. 1.—$\log (l_X)$ vs. $\log (l_b)$ is shown for all galaxy pairs. The filled hexagons are detected spiral pairs, the crosses are detected early-type galaxy pairs, the filled triangles are detected mixed pairs, and the open squares are upper limits for all pair types. Detected pairs with a Seyfert galaxy are represented by an open star. They are shown here but not included in correlations. The X-ray luminosities are given in the 0.25–2.0 keV energy band.

We ran correlation tests between $l_X$-$l_{\text{FIR}}$ and $l_X$-$\Delta r$ for the pair samples that have 36 and 49 pairs, respectively. The correlation test results are shown in Table 6; no strong correlation is present in either instance.

Figure 3 shows X-ray luminosity versus galaxy separation. Although the eye sees a trend of decreasing X-ray luminosity with decreasing separation, they are only weakly correlated (69%).

3.2. Spiral Galaxies

Twenty-five pairs of spiral galaxies are analyzed. The X-ray luminosities range from less than $2.6 \times 10^{40}$ to $10^{42}$ ergs s$^{-1}$. The $l_X$, $l_b$ for pairs is shown in Figure 4 along with $l_X$, $l_b$ for a sample of normal spiral galaxies taken from the

Fig. 2.—$\log (\text{observed } l_X)$ vs. $\log (l_{\text{FIR}})$ is shown for detections (filled hexagons) and upper limits (open squares). CPG 419 is detected as a Seyfert galaxy. It is shown as a star but not included in the correlations.

Fig. 3.—$\log (\text{observed } l_X)$ vs. $\log (\Delta r)$ is shown for detections (filled hexagons) and upper limits (open squares). Detected pairs with Seyfert galaxies are shown as stars. They are not included in the correlations.

Fig. 4.—$\log (l_X)$ vs. $\log (l_b)$ is shown for detected spiral galaxy pairs (filled hexagons), normal spiral galaxies (crosses), and spiral pair upper limits (open hexagons). Pair luminosities are converted to the energy band of the normal galaxies, 0.5–3 keV. CPG 419 is detected and has a Seyfert galaxy; it is shown by a star.
sample of galaxies observed with *Einstein* (Fabbiano, Gioia, & Trinchieri 1988; Trinchieri & Fabbiano 1985). The data are shown in the 0.5–3 keV band. Galaxies classified as \( T = 0.10 \) (very early type or irregular) were removed to get a representative sample of normal spirals. The pairs are converted from the *ROSAT* band using the canonical spectrum discussed in § 2 to derive luminosities. A value of \( H_0 = 50 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \) is used in both samples. \( l_X \) is lin-
early correlated with \( l_b \) on a log-log scale for the normal galaxy sample, greater than 99.9% confidence. We found the mean log \( l_X \) of the paired spirals to be \( 40.82 \pm 0.11 \, \text{ergs s}^{-1} \), higher than the mean value, \( 40.06 \pm 0.06 \, \text{ergs s}^{-1} \), predicted using the \( l_X-l_b \) relationship for isolated spirals observed with *Einstein*.

Peace & Sansom (1996) analyzed approximately 20 normal spiral galaxies observed with the PSPC. The galaxies in their sample have \( m_B < 13 \) and PSPC exposures greater than 13,000 s. They found a mean luminosity of \( \sim 10^{46} \). This mean is higher than that found for the entire sample observed with *Einstein* but similar to the value for
the subsample of optically bright galaxies. Using hardness ratios, these authors found that the PSPC spectra are consistent with a temperature of 0.85 keV and a range of 0.17–3.72 keV, suggesting that a softer component may also be present in addition to the hard component greater than 5 keV (Kim et al. 1992). ASCA observations of the spiral galaxy NGC 2903 (Mizuno et al. 1997) also show a hard, ~5 keV component and a soft ~0.4 keV component similar to the spectra they find for the starburst galaxies M82 and NGC 253. We performed a spectral analysis of all of the detected pairs. For most of the spiral galaxies, the data only provide lower limits to the temperature when fitting a Raymond & Smith model (see Table 5). Only for the spiral pair CPG 218, consisting of M81 and M82, is the 90% temperature range narrow, 0.7–1.1 keV. The best-fit temperatures are consistent with a softer X-ray component dominating the ROSAT emission as compared with Einstein. Thus, comparing with the sample in Peace & Sansom, the mean for spiral pairs, log $l_X = 40.82$ is significantly higher.

Similar conclusions resulted from a comparison of Einstein observations of a sample of normal galaxies with a sample of peculiar, blue galaxies. The sample of irregular galaxies had several galaxies with much higher $l_X/l_b$ than the normal galaxies (Fabbiano, Trinchieri, & MacDonald 1984). The irregular galaxies were chosen primarily for their blue color and in most cases display a disturbed morphology (Fabbiano, Feigelson, & Zamorani 1982).
3.3. Early-Type Galaxy Pairs

Eight early-type galaxy pairs are analyzed, of which three are detected with higher than 3 $\sigma$ significance. The sample of normal early-type galaxies observed with *Einstein* (Eskridge, Fabbiano, & Kim 1995a) is shown in Figure 5 with the best-fit line for comparison. A value of 50 km s$^{-1}$ Mpc$^{-1}$ for the Hubble constant was used in both samples, and the pair luminosities were converted to the energy band of the normal galaxies, 0.2–4 keV, using the canonical spectrum described in §2. These authors found that the sample is best characterized by two linear relations and those with $\log l_X > 40.5$ have a best-fit line with a steeper slope, $\approx 2$. This is attributed to X-ray emission from low-luminosity normal galaxies being dominated by low-mass X-ray binaries while the high-$l_X$ galaxies have a dominant contribution from hot gas. All of the pairs have $l_X > 40.5$: they are X-ray bright and fall into the latter category. Compared with the normal galaxies, the early-type pairs appear underluminous in X-rays for their $l_b$. We compare the observed $l_X$ for pairs with the sum of the predicted $l_X$ for each galaxy. The predicted $l_X$ is calculated from the $l_b$ for the galaxies individually, then added to get the predicted $l_X$ for the pair. The relationship reported by Eskridge et al. (1995a) for the brightest ellipticals, $l_X \sim l_b^2$, is used for the predicted values. Figure 6 shows that the observed values systematically fall below the predicted values, except in the case of the detected pair, CPG 564, for which we report evidence of an intergalactic medium ($\sim 4$). The mean predicted is $\log l_X = 42.10 \pm 0.19$: 2 $\sigma$, 95% confidence, higher than the mean observed value of the pairs, $41.35 \pm 0.21$. If CPG 564 is excluded, the mean observed $\log l_X$ decreases to $41.16 \pm 0.12$ and the difference increases to 3 $\sigma$.

The blue magnitudes from Karachentsev (1972) are isophotal and extend to the $B \approx 26$ mag arcsec$^{-2}$ isophote. This is 1 mag fainter than the limiting value in RC2, which was used in the comparison sample of early-type galaxies in Eskridge et al. (which is based on Fabbiano et al. 1992). The NED database was used to obtain the RC3 (de Vaucouleurs et al. 1991) magnitudes for the brightest galaxy in the eight pairs. The magnitudes from the CPG and RC3 are both corrected for extinction in the Milky Way. The CPG pairs are additionally corrected for internal extinction based on galaxy type and inclination. The values are listed for comparison with the CPG magnitude given first: CPG 18 (14.78, 14.60), CPG 90 (15.39, 15.7), CPG 99 (12.91, 12.61), CPG 175 (13.21, 12.12), CPG 320 (14.49, 14.9), CPG 367 (14.52, 13.64), CPG 564 (14.63, 14.32), and CPG 574 (13.98, 13.63). The RC3 values for CPG 18, CPG 90, and CPG 320 are not corrected for extinction and CPG 90 and CPG 320 are a little high. For all of the other pairs the RC3 magnitude is slightly lower; generally all of the pairs agree within the published RC3 error. The trend reported in this paper, that early- and mixed-type pairs have a lower $l_X$ for their $l_b$
Fig. 16.—Contour map of CPG 99 is shown for image smoothed with a Gaussian of width 22.5''. Contour levels are 2 and 3 $\sigma$.

(based on the CPG) cannot be explained as a systematic overestimate of the $I_0$ from CPG relative to the RC3, on which the comparison sample is based. In both Figures 5 and 6, use of the RC3 magnitudes for the paired galaxies would generally shift the pairs to the right, making the underluminosity more evident.

The process of disk galaxy merger can give a blue luminosity much higher than is typical of even the brightest isolated galaxies (Caon et al. 1994). High-$I_0$ galaxies occupy a region of the fundamental plane consistent with mergers of systems that are generally less gaseous and more stellar (Bender, Burstein, & Faber 1992). Thus, those galaxies that have a high $I_0$ are associated with interaction and in some cases, merger. The very high $I_0$ early-type pairs are also characterized by a low X-ray luminosity similar to NGC 4125 and NGC 3610. These galaxies also have low 0.1–2 keV X-ray luminosities and have plumes of emission suggesting the later stages of a merger (Fabbiano & Schweizer 1995). The prototype for the pairs is the close elliptical pair, CPG 99, found to show evidence of tidal interaction in the form of a U-shaped velocity dispersion (Borne & Hoessel 1988; Bonfanti et al. 1995). In addition, the galaxy NGC 1587, which is part of the pair, was argued to be a merger remnant on the basis of an angular momentum that could not be attributed to the present interaction. The CPG 99 pair is detected at greater than 3 $\sigma$ and has a low $L_X$, less than $10^{41}$ erg s$^{-1}$, for its $I_0 \sim 2 \times 10^{44}$ erg s$^{-1}$. The early-type pairs typically have low $L_X$ and may show evidence of being merger remnants as well as interaction with their companion. The NGC 4782/4783 pair (Colina & Borne 1995) also shows a low integrated X-ray luminosity, $\sim 2 \times 10^{41}$ erg s$^{-1}$, typical of the underluminous pairs found here. High-resolution studies of the 4782/4783 system show multiple X-ray components resulting from the interaction and merger of the two galaxies, which includes tidal heating and shock heating from the collision. This detailed study supports the hypothesis that in the underluminous pairs the X-ray emission is directly associated with the interaction/merger. The spatial analysis presented in § 4 contained CPG 99 and CPG 564. CPG 99 is underr
luminous by nearly a factor of 10, the least X-ray luminous
detection. The spatial analysis shows that it has a very small
radial extent of \(\sim 47\) kpc and a small core radius when
compared with similar parameters for groups. For example,
the NGC 2300 group has a radial extent of more than 250
kpc. In contrast, the only pair with a luminosity over that
predicted, CPG 564, has X-ray emission extending to more
than 169 kpc, which is likely intergalactic. The gas tem-
perature is \(1.03^{\pm0.26}\) keV, similar to that found for groups.
If the underluminous early-type galaxy pairs such as CPG
99 are merger remnants, then they must have formed out of
spiral pairs with no intergalactic medium. Generally, these
are the low-velocity dispersion groups (Mulchaey et al.
1996). Spectral fits performed on five detected paired gal-
axies gave significant temperature constraints with best-
fitting temperatures between 0.20 and 1.26 keV; in all cases
the 90% range in temperature excludes a hard component
dominating the emission. Thus, the spectrum is dominated
by hot gas. \textit{ASCA} and \textit{ROSAT} spectra of normal elliptical
galaxies show both a hard component, with \(l_X\) correlated
with \(l_b\) (Matsushita et al. 1994) implying a stellar origin, and
a soft component, which dominates the emission of bright
ellipticals (Fabbiano, Kim, & Trinchieri 1994; Kim et al.
1996). The soft component originates in hot gas with the
most X-ray luminous normal ellipticals being consistent in
their \(l_X-l_b\) relationship with a steady state cooling flow
(Sarazin & Ashe 1989).

The gasdynamics in normal elliptical galaxies fits a some-
what simple picture in which the temperature of the hot gas
component is proportional to the velocity dispersion of the
galaxy but is not in energy equipartition with the stellar
component, implying that the gas is heated and bound by
the dark matter-dominated gravitational potential (Davis
& White 1996; Eskridge, Fabbiano, & Kim 1995b). Studies
of several pairs show that they are dynamically complex
with U-shaped velocity dispersion profiles, presumably
from tidal heating in the outer radii. Analogous to the stars,
the gas would also be tidally heated. Tidally triggered
dynamical heating as well as that from star formation may
be sufficient to overcome the binding gravitational potential

Fig. 17.—Contour map of CPG 234 is shown for image smoothed with a Gaussian of width 22.5'. Contour levels are 3, 5, and 10 \(\sigma\).
of the galaxy. This would account for the paired galaxies being among the least luminous of those normal early-type galaxies that are classified as X-ray luminous and dominated by hot gas. Simple calculations by Mathews & Brighenti (1997) suggest that a factor of ~10 underluminous interacting early-type galaxies must be recent merger/interactions, ~10^9 yr, because of replenishment of the interstellar gas by stellar mass loss. This would make gas deficiency an unlikely explanation for a large number of low-l_X/l_b galaxies on statistical grounds. Figure 5 indicates that approximately half of the pairs are underluminous by a factor of 10 compared with the best-fit linear regression found for normal early-type galaxies. However, paired galaxies are expected to show a higher frequency of recent and ongoing interaction/merger than single galaxies, so that gas lost may not have been fully replenished by stellar mass loss.

Galaxies in early-type pairs show evidence of interaction and merger based on very high blue luminosities and disturbed velocity dispersion profiles. They also tend to be deficient in X-rays which, because of their soft spectra, indicate a deficiency in hot gas. This may have important consequences for enrichment of the intergalactic medium with metals. One of the ways in which nonisolated galaxies evolve, whether the environment is a pair, group, or cluster, may be through interactions with another galaxy. Interaction with a companion appears to destabilize gas within the pair system so that it cannot be bound by the galaxies. If the pairs are in a cluster or group environment, the intergalactic medium would be enriched during the merger process since the more massive system would be able to bind the gas. These results would apply equally well to a cluster of protogalaxies in which recent observations of cluster abundances imply that the enrichment must occur (Mushotzky & Loewenstein 1997).

3.4. Mixed-Type Galaxy Pairs

There are 16 mixed morphology pairs, of which three are detected at greater than 3σ. Figure 7 shows observed l_X versus predicted l_X in the 0.2–4 keV band. The predicted

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**Fig. 18.**—Contour map of CPG 239 is shown for image smoothed with a Gaussian of width 22'. Contour levels are 1, 2, and 3σ.
values are the sum of the individual values predicted for each galaxy using the $l_x-l_b$ appropriate for each galaxy class. There are eight pairs: two detections and six upper limits, with luminosities below that predicted. Four (two detections and two upper limits) are significantly underluminous. A spatial analysis of the two detections, CPG 278 and CPG 353, shows emission centered on both galaxies in the case of CPG 278 and on the elliptical in the case of CPG 353. The 90% confidence range in temperature for CPG 278 is 0.31–0.57 keV, lower than all of the groups reported by Mulchaey et al. (1996). The temperature of CPG 353 is 0.78–0.85 keV; however, both have X-ray emission about a factor of 10 below that predicted for their $l_x$. They are underluminous in the same sense that the early-type pairs are underluminous; they are gas-poor galactic systems and lack an additional intergalactic component.

4. SPATIAL ANALYSIS

Eight detections (excluding those dominated by AGNs) are located in an appropriate region of the detector and have sufficient counts for spatial analysis: CPG 234, CPG 239, CPG 278, and CPG 353 (mixed pairs), CPG 99 and CPG 564 (early-type), and CPG 125 and CPG 218 (spiral pairs). The PSPC images were flat-fielded, corrected for vignetting, and background subtracted prior to further analysis.

Radial profiles were made using the X-ray peak as the center (Figs. 8–15). These are used to obtain the extent of the X-ray emission. X-ray contours are overlain on the DSS image (Figs. 16–21) to see the relationship between the X-ray emission and the galaxies. The contours are smoothed with a Gaussian of width 22.5, chosen to minimize the confusion between close galaxy pairs.

From the radial profiles, the peak surface brightness and HWHM is measured, as well as the approximate radial extent. For CPG 125, 218, and 278, the emission is resolved into two distinct components: one centered on each galaxy. There is an entry in Table 8 for each galaxy in these pairs. Intergalactic group X-ray emission is typically fit by a $\beta$ of 0.5 using the radial profile, $[1 + (r/r_s)^2]^{-3\beta+0.5}$. For this

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Fig. 19.—Contour map of CPG 278 is shown for image smoothed with a Gaussian of width 22.5. Contour levels are 3, 5, and 10 $\sigma$. 
Table 8

X-RAY SPATIAL RESULTS

| CPG    | Peak Surface Brightness | HWHM (kpc) | Radial Extent (kpc) |
|--------|-------------------------|------------|---------------------|
| 99     | 3.6                     | ~14        | ~47                 |
| 125    | 24.7                    | 5          | 17                  |
| 218    | 14.5                    | 1          | 2                   |
| 234    | 7.9                     | 15         | 40                  |
| 239    | 13.0                    | 32         | 74                  |
| 278    | 12.6                    | 2          | 7                   |
| 353    | 471.0                   | 2          | 6                   |
| 564    | 1.4                     | 80         | ~169                |

Note: Peak surface brightness in units of $10^{-3}$ counts s$^{-1}$ arcmin$^{-2}$.

The HWHM of CPG 125 and CPG 218, the spiral pairs, is consistent with a point source, while for the other six pairs the emission is extended. This comparison was made allowing for the broadening PSF of the PSPC with radius. The HWHMs for the pairs with extended emission are generally smaller than the core radii of groups. The extent of the gas is much smaller than groups, except in the case of CPG 564. CPG 564 is for the most luminous early-type pair, $4.7 \times 10^{42}$ ergs s$^{-1}$ and comparable to the brightest in the survey of isolated galaxies. The extent of its X-ray emission, greater than 169 kpc, and HWHM, ~80 kpc, is comparable to that from an intergalactic medium. However, the X-ray profiles of the other five indicate galactic emission.

The X-ray emission originating from hot gas in early- and...
mixed-type pairs shows that they are generally underluminous in X-rays compared with that expected from isolated galaxies. There is also no spatial evidence that these optically selected pairs have intergalactic gas similar to the NGC 2300 system. If the early- and mixed-type galaxies formed through mergers, they must have formed from spiral-rich groups with little or no intergalactic medium. These are generally groups with a low velocity dispersion (Mulchaey et al. 1996).

5. CONCLUSIONS

We have completed the first X-ray survey of optically selected galaxies in pairs using ROSAT pointed observations. An analysis of the hot gas content in early- and mixed-type galaxy pairs indicates that they are generally characterized by a lower $l_X$ for their $l_b$ compared with normal galaxies. A spatial analysis indicates that the extent of the X-ray emission is much less than the intergalactic medium of a group and is centered on a galaxy. This is consistent with X-ray emission being galactic in origin. The mean $l_X$ for early-type pairs is 2 $\sigma$, 95% confidence, lower than the mean predicted if they were isolated galaxies implying that they are gas poor. Mixed pairs show this same trend. The X-ray brightest pair, CPG 564, is an exception to this trend since a spatial and spectral analysis shows that its emission is likely intergalactic. These pairs show evidence of interaction and possibly merger in other wavebands. If they have formed through mergers, then the lack of any intergalactic emission could be explained if they formed out of spiral-dominated, low velocity dispersion groups. These typically have no intergalactic medium.

The spiral galaxy pair sample has a number of pairs with significantly higher $l_X/l_b$ than the normal galaxy sample, comparable to the brighter starburst galaxies and less luminous Seyfert galaxies.

X-ray studies of galaxies in pairs are of fundamental importance to understanding the impact of interacting galaxies on galaxy evolution. Enrichment of the intergalactic
medium may also be tied to protogalactic interactions and gas loss as reported here for early- and mixed-type pairs. The relationship between the X-ray emission of pairs and galaxy groups of 3–4 members is also crucial for understanding the dynamical history of the groups and any dependence on morphology. Future detailed studies of individual pairs of each galaxy type that provide spatially and spectrally resolved X-ray components are necessary to discover the detailed interaction history of these interesting objects.

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