THE X-RAY EVOLUTION OF HICKSON COMPACT GROUPS

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ABSTRACT

The Hickson compact groups, displaying regions of high galaxy densities, should provide environments where galaxy evolution occurs rapidly. The repeated galaxy interactions and mergers present in compact groups increase the rate of star formation and increase the number of X-ray binaries. A fraction of the H$^i$ gas will also become heated via stirring and shocks, which yields extended diffuse, hot gas halos that can encompass all members of a compact group. Using a sample of 16 Hickson compact groups from the Chandra X-Ray Observatory archives, we report on a correlation between the diffuse X-ray gas and the total X-ray point source population luminosities. The correlation of the X-ray gas and point source luminosities is further examined to establish a general evolutionary trend.

Key words: galaxies: evolution – X-rays: binaries – X-rays: galaxies

1. INTRODUCTION

Galaxies in close configurations experience increased gravitational interactions and large-scale perturbations which provide ideal laboratories for the study of galaxy evolution. The high-density environments and the relatively low velocity dispersions of the Hickson compact groups (HCGs) indicate that these systems should evolve on rapid timescales (Walker et al. 2010). The study of HCGs began with their photometric and spectroscopic classification by Hickson (1982). Since that time, multiple in-depth studies over numerous wavelength regimes have focused on the HCG systems (Pildis et al. 1995; Ponman et al. 1996; Martinez-Badenes et al. 2012). Investigations on the evolution of the HCGs have focused on neutral and molecular hydrogen, star formation, and nuclear activity observed in these systems. Coziol et al. (1998) suggest that the evolution of HCGs is driven by increased mergers and gas stripping. A quantitative measure of the evolutionary state of HCGs was defined by Coziol et al. (2004) using an activity index and the morphologies of the individual group members. The mean activity index and the mean morphological type delineates the HCGs into three classes of evolution. The least evolved groups were observed to have low velocity dispersions ($\sigma < 300$ km s$^{-1}$) and actively star forming spiral galaxies, while the most evolved groups were elliptical-galaxy-dominated systems with high velocity dispersions.

Verdes-Montenegro et al. (2001) developed an evolutionary sequence for HCGs similar to that proposed for the Toomre sequence mergers (Toomre & Toomre 1972). Phase 1 of the Verdes-Montenegro et al. (2001) evolutionary sequence found the H$^i$ distribution to be relatively unperturbed and more than 90% of the H$^i$ mass was found within the individual galaxies. In Phase 2, 30%–60% of the total H$^i$ mass forms tidal features. In the final stage of evolution, Phase 3, most of the H$^i$ has been stripped from individual galaxies. HCGs in Phase 2 or 3 have been observed to have diffuse X-ray gas halos, which is theorized to be due to the heating of the stripped H$^i$ gas (Pietsch et al. 1997; Desjardins et al. 2012).

The work of Verdes-Montenegro et al. (2001) has been extended to examine the effects of H$^i$ in the HCGs on infrared star formation rates, molecular hydrogen deficiency, and X-ray emission (Johnson et al. 2007; Borthakur et al. 2010; Martinez-Badenes et al. 2012; Desjardins et al. 2012). The results of these studies are consistent with the notion that the most H$^i$-poor compact groups are not missing gas, rather the H$^i$ gas has been used to fuel star formation as well as having been extracted from the individual galaxies and converted to intergroup X-ray gas (Rasmussen et al. 2008; O’Sullivan et al. 2009). The presence of intergroup X-ray gas has previously been used to assess the evolutionary state of a group (Jeltema et al. 2008).

The interactions between galaxies in a compact group result in a fraction of the H$^i$ within group members to be stripped and deposited into the intergroup medium. The gas can then be stirred and shocked, heating the intergroup gas to X-ray temperatures. Simultaneously, the galaxy interactions cause the fraction of H$^i$ gas remaining within the group members to fuel star formation, which results in high-mass X-ray binaries (HMXBs) and increases the rate of low-mass X-ray binary (LMXB) formation (Fragos et al. 2008). As the galaxies within a compact group move closer to coalescence, the luminosities of the X-ray binary population and of the diffuse X-ray gas should increase.

The purpose of this work is to present the relation between X-ray gas luminosity and group point source X-ray luminosity for a sample of 16 HCGs observed with the Chandra X-Ray Observatory. The evolution of the HCGs is cross-referenced with the classification of Coziol et al. (2004) and Verdes-Montenegro et al. (2001). The selection and properties of the HCG sample and the reference elliptical and group samples are presented in Section 2. Data reduction and analysis techniques are discussed in Section 3. Sections 4 and 5 detail the results and conclusions. A Hubble constant of $H_0 = 72$ km s$^{-1}$ Mpc$^{-2}$ is adopted throughout the paper.

2. THE SAMPLE

2.1. Hickson Compact Groups

All HCGs in the Chandra archive prior to 2011 May were selected. The sample includes 16 HCGs spanning the evolutionary sequence. The sample contains compact groups theorized to be young, with weak X-ray features, spiral-dominant
morphologies, and active star formation, as well as evolved systems displaying strongly interacting members, early-type morphologies, and X-ray bright halos. The physical properties of the HCGs are listed in Table 1.

2.2. Reference Samples

Reference samples of elliptical galaxies and non-compact groups were identified. The reference groups were randomly selected from the X-ray Atlas of Groups of Mulchaey et al. (2003). Non-compact groups displaying similar redshift range, group membership, and spiral fraction to the HCG sample were selected. The reference sample of elliptical galaxies were randomly selected from galaxies in the study of Diehl & Statler (2007) that also have listed spectroscopic age determinations from Terlevich & Forbes (2002). A total of eight groups and five elliptical galaxies comprise the reference samples. Tables 2 and 3 list the physical properties of the reference systems.
3. DATA REDUCTION AND ANALYSIS

The HCG and the reference samples were observed with the Chandra Advanced CCD Imaging Spectrometer (ACIS-S). The data were reduced using CIAO 4.3 (Fruscione et al. 2006) and CALDB version 4.4.1, following the standard data processing. Beginning with the level 1 event file, the data were reprocessed to include the latest tools to redetect hot pixels, afterglow events, and to apply the most recent gain file. The level 2 event file was further filtered, retaining only events with ASCA grades 0, 2, 3, 4, and 6.

3.1. Diffuse Gas

In order to analyze the diffuse gas, point sources were first detected using the CIAO tool, wavdetect. Point source regions were removed and filled via a linear interpolation using the CIAO tool, dmfilth. Source regions were filled using the counts in background regions of radii equal to twice the point source region radii. The point source-removed images were smoothed to highlight the diffuse emission. Figure 1 displays an image of the diffuse gas contours of the HCG 92 system (left panel).

Spectra were extracted for the unsmoothed diffuse emission in regions that extended to X-ray surface brightnesses 1.5σ above the background, similar to the procedure of Saracco & Ciliegi (1995) for ROSAT observations of HCGs. For HCG and non-compact groups where there is no intergroup medium and the diffuse halos are confined to the individual group members, spectra of each halo were taken individually and the fluxes were summed to yield the total group diffuse gas X-ray luminosity. Background spectra were extracted from annular regions surrounding the source regions. To determine the X-ray flux of the diffuse gas, as well as for obscured point sources, spectra were fit with a two-component model comprised of either a thermal Meka model (Mewe et al. 1985) or thermal APEC model (Smith et al. 2001) and a power law. Spectra were fit in the 0.3–6.0 keV range. During the spectral fitting, the neutral hydrogen column density was fixed to the Galactic value, while the temperature was allowed to vary.

3.2. Point Sources

Point sources associated with each compact group were analyzed to determine the group total point source X-ray luminosity. Point sources were determined as associated with the group by selecting all sources within the $R_{25}$ radius or within the 1.5σ extent of the diffuse halo. The sources were cross-correlated with the Tycho-2 Catalog (Hog et al. 2000) and the Hipparcos Catalog (Perryman et al. 1997) in order to identify Galactic sources contaminating the HCG sample associated point source population. The astrometric errors at the center of the Chandra field are likely ∼0.5″, with larger errors at the field edge.

In order to account for any background active galactic nucleus (AGN) contamination in the sources detected beyond the $R_{25}$ radius of galaxy members, we have followed the method employed by Bogdan et al. (2012). Using three annuli (10″, 20″, and 30″) surrounding the $R_{25}$ radius of sample galaxies, the cosmic X-ray background (CXB) source density was calculated. Sources within the $R_{25}$ radius were excluded. The log $N$–log $S$ distribution of Georgakakis et al. (2008) was used to determine the CXB source density. In order to convert the 0.5–10 keV band log $N$–log $S$ distribution of CXB sources to the 0.5–8 keV energy range, we assumed a power law model with a slope of $\Gamma = 1.4$. Figure 2 displays the average source density of the HCGs and the expected density of CXB sources. All of the HCGs have source densities well in excess of the expected background contribution. The point sources detected beyond the $R_{25}$ radius of individual group members may be LMXBs residing in globular clusters existing in the dark matter halo of the group (Bogdan et al. 2012).

We applied apertures on the coordinates from the output of the CIAO tool, wavdetect. Spectra were extracted for each point
Table 4

X-Ray Properties of the Hickson Compact Group Sample

<table>
<thead>
<tr>
<th>Group</th>
<th>Log Gas $L_X$ (erg s$^{-1}$)</th>
<th>Log Pt Src $L_X$ (erg s$^{-1}$)</th>
<th>Activity Index</th>
<th>H I Phase</th>
<th>X-Ray Evolutionary State</th>
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<tbody>
<tr>
<td>7</td>
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<td></td>
<td>1</td>
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</tr>
<tr>
<td>16</td>
<td>41.3</td>
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<td>2</td>
<td>Intermediate</td>
</tr>
<tr>
<td>22</td>
<td>40.9</td>
<td>40.7</td>
<td>B</td>
<td>3</td>
<td>Intermediate</td>
</tr>
<tr>
<td>30</td>
<td>39.9</td>
<td>38.5</td>
<td></td>
<td>3</td>
<td>Early</td>
</tr>
<tr>
<td>31</td>
<td>41.6</td>
<td>41.1</td>
<td></td>
<td>2</td>
<td>Advanced</td>
</tr>
<tr>
<td>37</td>
<td>41.1</td>
<td>40.5</td>
<td></td>
<td>3</td>
<td>Intermediate</td>
</tr>
<tr>
<td>40</td>
<td>40.8</td>
<td>40.0</td>
<td>B</td>
<td>2</td>
<td>Early</td>
</tr>
<tr>
<td>42</td>
<td>41.7</td>
<td>40.6</td>
<td></td>
<td>3</td>
<td>Intermediate</td>
</tr>
<tr>
<td>51</td>
<td>42.2</td>
<td>40.9</td>
<td></td>
<td></td>
<td>Advanced</td>
</tr>
<tr>
<td>59</td>
<td>40.7</td>
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<td>41.0</td>
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<td>Intermediate</td>
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<tr>
<td>80</td>
<td>41.5</td>
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<tr>
<td>90</td>
<td>40.4</td>
<td>39.9</td>
<td>B</td>
<td>3</td>
<td>Early</td>
</tr>
<tr>
<td>92</td>
<td>41.7</td>
<td>41.6</td>
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<td>3</td>
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</tr>
<tr>
<td>100</td>
<td>41.1</td>
<td>39.9</td>
<td></td>
<td>2</td>
<td>Early</td>
</tr>
</tbody>
</table>

Notes. Column (1) Hickson Compact Group number. Columns (2) and (3) The logarithm of the diffuse gas and total point source X-ray luminosities, respectively. Column (4) Activity index as defined by Coziol et al. (2004). Coziol et al. type A groups are defined by spiral morphologies and active star formation. Type C groups are characterized by elliptical morphologies and high velocity dispersions. Column (5) H I gas phases defined by Verdes-Montenegro et al. (2001) and Borthakur et al. (2010). Phase 1 HCGs display a relatively unperturbed H I and more than 90% of the H I mass is detected in the individual galaxies. HCGs in Phase 3 have had most of the H I stripped from the individual galaxy members. Column (6) Evolutionary state defined using the $L_{X,\text{Gas}}$–$L_{X,\text{Pt.srcs}}$ relation. The early X-ray state is defined as $\log L_{X,\text{Gas}} \leq 41.1$ erg s$^{-1}$ and $\log L_{X,\text{Pt.srcs}} \leq 40.4$ erg s$^{-1}$. HCGs identified in an advanced X-ray evolutionary state display $\log L_{X,\text{Gas}} \geq 41.6$ erg s$^{-1}$ and $\log L_{X,\text{Pt.srcs}} \geq 40.9$ erg s$^{-1}$.

Figure 2. Average density of resolved sources in three annuli around the HCG galaxy members. The solid line displays the expected number of CXB sources within each annulus.

source associated with sample galaxies. Background spectra were extracted from annular regions surrounding the point sources. Again, spectra were fit using a two-component model comprised of a power law or broken power law to account for the point source emission and a thermal bremsstrahlung model to account for any diffuse gas within the point source region. Spectra were fit in the 0.3–6.0 keV range.

The fluxes for all point sources associated with a sample galaxy or group were summed in order to determine the group’s total galaxy point source luminosity. It should be noted that the brightest X-ray point source located in the center of member galaxies were excluded when calculating the total point source luminosity, in order to avoid the influence of any AGN. An image of the point source population of HCG 92 (right panel) is displayed in Figure 1.

The nature of the individual point sources were examined by determining the total counts in three energy bands; the soft band (0.3–1 keV), the medium band (1–2 keV), and the hard band (2–8 keV). The counts in the three bands were used to calculate the hard and soft X-ray colors. The X-ray colors are defined as (Prestwich et al. 2003),

\[
\begin{align*}
\text{Soft Color} &= (M - S)/T \\
\text{Hard Color} &= (H - M)/T,
\end{align*}
\]  

where S, M, H, and T are the soft, medium, hard, and total counts, respectively. A plot of X-ray soft color versus X-ray hard color can be used to classify point sources into HMXBs and LMXBs.

4. RESULTS

The derived X-ray luminosities for the diffuse gas halos and the point source population of the HCGs are presented in Table 4. The HCGs span a narrow range in $\log L_{X,\text{Gas}}$ (39.9–42.2 erg s$^{-1}$) and $\log L_{X,\text{Pt.srcs}}$ (38.5–41.6 erg s$^{-1}$). The X-ray luminosities for the reference samples are presented in Table 5. The elliptical galaxy and group reference samples span similar X-ray luminosity ranges as the HCGs.

While there does not appear to be significant variation for the sample of HCGs, the relation between the $L_{X,\text{Gas}}$ and $L_{X,\text{Pt.srcs}}$ values yields an interesting result. Figure 3 displays the X-ray gas luminosity–X-ray point source population luminosity relation. As can be seen in Figure 3, the two X-ray luminosities are
Figure 3. Diffuse gas–point source population X-ray luminosities relation. The line is a least-squares fit to these data. The observed trend yields an evolutionary classification, where more evolved compact groups display larger X-ray luminosities for both the X-ray point source population and the diffuse gas halo.

Table 5

X-Ray Properties of the Reference Samples

<table>
<thead>
<tr>
<th>Group</th>
<th>Log Gas $L_X$ (erg s$^{-1}$)</th>
<th>Log Pt Src $L_X$ (erg s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
</tr>
<tr>
<td>Group Sample</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 315</td>
<td>40.3</td>
<td>40.6</td>
</tr>
<tr>
<td>NGC 741</td>
<td>41.0</td>
<td>40.8</td>
</tr>
<tr>
<td>NGC 1587</td>
<td>40.4</td>
<td>39.6</td>
</tr>
<tr>
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</tr>
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<td>NGC 3665</td>
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<td>38.6</td>
</tr>
<tr>
<td>NGC 4325</td>
<td>42.1</td>
<td>40.8</td>
</tr>
<tr>
<td>RXC J1320.2+3308</td>
<td>41.7</td>
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</tr>
<tr>
<td>NGC 6338</td>
<td>41.7</td>
<td>40.6</td>
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<tr>
<td>Elliptical Galaxy Sample</td>
<td></td>
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<tr>
<td>NGC 3585</td>
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</tr>
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<td>NGC 1399</td>
<td>41.4</td>
<td>38.5</td>
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</table>

Notes. Column (1) Group or Galaxy Name. Columns (2) and (3) The logarithm of the diffuse gas and total point source X-ray luminosities, respectively.

correlated, indicating that an increased diffuse halo luminosity corresponds to an X-ray luminous point source population. A linear least-squares fit to these data, with a slope of 0.65 ± 0.14, is plotted in Figure 3. The data in Figure 3 were determined to have a correlation coefficient of 0.80.

The $L_{X,Gas}$ and $L_{X,Pt.srcs}$ trends for the reference samples are displayed in Figure 4. The elliptical galaxies and groups are displayed as squares and triangles, respectively. There does not appear to be a correlation between the gas and point source X-ray luminosities for the elliptical galaxies. A weak correlation may exist for the reference group sample; however, the correlation between $L_{X,Gas}$ and $L_{X,Pt.srcs}$ displays a significantly larger scatter than that observed for the HCG sample. The groups displayed in Figure 4 have a correlation coefficient of 0.39.

Based on the Coziol et al. (2004) measure of HCG evolutionary state, groups containing a larger fraction of early-type galaxies are more evolved. In order to assess the possibility that the changing morphological distribution within each HCG causes the $L_{X,Gas}$–$L_{X,Pt.srcs}$ trend observed in Figure 3, the relation of spiral fraction with both the point source and diffuse gas X-ray luminosities is investigated. Figures 5 and 6 display the HCG and reference group relation between spiral fraction and the diffuse X-ray gas and the point source population X-ray luminosities, respectively. From Figure 5, the morphological content of the HCGs and groups does not appear to affect the X-ray luminosity of the diffuse gas halos. As seen in Figure 6, there is no obvious trend between the point source X-ray
luminosity and spiral fraction for the HCGs. The reference group sample does display a weak correlation, where the point source luminosity increases with increasing spiral fraction.

We have provided estimates of each group’s evolutionary state based on the trend of Figure 3. It is important to note that evolution occurs on a continuum and we can state that HCGs having low X-ray luminosities are less evolved than their counterpart systems displaying high gas and point source X-ray luminosities. Using the relation of Figure 3, we chose to classify the HCGs broadly as early, intermediate, or advanced states of evolution. An early X-ray evolutionary state is defined as log \( L_{X,Gas} \leq 41.1 \text{ erg s}^{-1} \) and log \( L_{X,pt,srcs} \leq 40.4 \text{ erg s}^{-1} \). HCGs identified in an advanced X-ray evolutionary state display log \( L_{X,Gas} \geq 41.6 \text{ erg s}^{-1} \) and log \( L_{X,pt,srcs} \geq 40.9 \text{ erg s}^{-1} \).

There is no combination of previous studies that estimate the evolutionary stage of all of the HCGs presented here. The Coziol et al. (2004) activity index, the H\(_{\text{i}}\) phases (Verdes-Montenegro et al. 2001; Borthakur et al. 2010), and our estimated X-ray evolutionary state are presented in Table 4. Using the trend observed in Figure 3, we determined that HCGs 31, 51, and 92 display the highest level of evolution for our sample. The advanced states of evolution observed for these systems are consistent with the results of Mendes de Oliveira & Carrasco (2007) in a study on the connection between fossil and compact groups.

A note of caution is needed when comparing the Coziol activity index, the H\(_{\text{i}}\) phase, and the X-ray evolutionary state. Each of these assessments measure properties that can evolve on different timescales. HCG 90 provides an example of these different timescales. With an activity index of B, a Phase 3 H\(_{\text{i}}\) distribution, and an X-ray state of early evolution, HCG 90 appears to have contradictory results. However, it is possible that the H\(_{\text{i}}\) gas has been deposited into the intergroup region (Phase 3), which has decreased star formation (activity index B), while the intergroup H\(_{\text{i}}\) has not yet been heated (early X-ray state).

Figure 7 displays an X-ray color–color plot for the point sources in the HCGs. The symbols displayed in Figure 7, circles, X’s, and triangles, correspond to sources in HCGs in advanced, intermediate, and early X-ray states, respectively. The green circle identifies the region typically occupied by HMXBs. The vertical region at the X-ray hard color of \( \sim -0.2 \) between X-ray soft colors of \([-0.5, 0.0]\) delineates the region of LMXBs. Approximately 25% of the point sources in the advanced and intermediate X-ray states have colors consistent with HMXBs. The early X-ray state HCGs are comprised of 9% of sources that would be classified as HMXBs.

5. CONCLUSIONS

We have analyzed a sample of HCGs observed with the Chandra X-Ray Observatory to gain an understanding of the relation between X-ray gas halos, the X-ray point source population and a group’s state of evolution. The close galaxy configurations found in the HCGs provides an environment where galaxy interactions and mergers should occur on a short timescale. Therefore, it should be possible to determine an HCG’s state of evolution using a variety of techniques. Here we demonstrate a novel evolutionary correlation between the X-ray luminosities of diffuse gas and point source population of HCGs.

The data presented in Table 4 and Figure 3 indicate that as the X-ray halo grows, a compact group will also experience an increase in the X-ray luminosity of the point source population. This scenario is consistent with the interactions in compact groups redistributing a portion of the H\(_{\text{i}}\) gas. The subsequent stirring of the intergroup gas by member galaxies interacting and colliding heats the gas to X-ray temperatures. H\(_{\text{i}}\) gas that is not heated can cause increased star formation in the individual galaxies, resulting in a population of X-ray binary point sources (White & Ghosh 1998; Wu 2001). While star formation can build the population of short-lived HMXBs, the rate of LMXB formation will also be increased. The rate of LMXB formation is predicted to decrease with time 1 Gyr after a star formation event (Fragos et al. 2008). As interactions are continually occurring in the HCGs, the X-ray point source population should build up
until the group members coalesce. Figure 7 is also consistent with the notion that interactions have enhanced the HMXB and LMXB populations of the most evolved HCGs.

We have examined whether the observed $L_{X,\text{Gas}} - L_{X,\text{pt.srcs}}$ correlation is due to the changing morphological composition of compact groups. As HCGs evolve, the fraction of spiral galaxy members should decrease. Figures 5 and 6 highlight the lack of correlation between $L_{X,\text{Gas}}$ or the $L_{X,\text{pt.srcs}}$ with spiral fraction. The morphological composition does not appear to be the underlying cause of the $L_{X,\text{Gas}} - L_{X,\text{pt.srcs}}$ trend observed in Figure 3. We hypothesize that the increased interactions amongst HCG members is the cause of the trend.

The reference galaxy sample does not display the $L_{X,\text{Gas}} - L_{X,\text{pt.srcs}}$ correlation, as seen in Figure 4. The reference group sample displays a weak trend, with a significantly larger scatter than observed for the HCGs. We hypothesize that the $L_{X,\text{Gas}} - L_{X,\text{pt.srcs}}$ trend, observed in Figure 3, is strongest in merging and recently merged systems, where interactions will be sustained and ongoing processes. Future work will examine the X-ray gas and point source populations across the merging sequence in order to better understand the evolution of the diffuse gas and point source population X-ray luminosity trend described here. Specifically, we will examine Toomre sequence galaxies as well as the theorized remnants of compact groups, isolated ellipticals and fossil groups.

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