FINDING FOSSIL GALAXY SYSTEM PROGENITORS
USING STRONG GRAVITATIONAL LENSING

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ABSTRACT

Fossil galaxy systems have been described as some of the oldest systems in the universe, where the central galaxy has cannibalized most nearby member galaxies over cosmic time. While the progenitors to fossil systems have been predicted to exist in numerical simulations, little effort has gone into locating them until now. The discovery of fossil progenitors in the CASSOWARY catalog of strong gravitational lensing demonstrates that not all fossils are old, and their formation histories are more complex than originally thought. These progenitors have optical characteristics consistent with them being the transition phase between non-fossils and fossils, as we are observing the central galaxies in mid-assembly. We also identify a bias where systems acting as strong gravitational lenses are \( \sim 5 \) times more likely to be seen as fossils than non-lensing systems. Chandra X-ray images of eight CASSOWARY fossil progenitors show them being significantly over-luminous and hotter than comparable non-fossils which could be due to the strong lensing bias in our data, or fossils have characteristically deeper potential wells than non-fossils. Two progenitors were luminous enough to see a rise in gas temperature toward their cores which suggests these may be undergoing group mergers akin to the previously studied progenitor CSWA 2 verifying this as a viable fossil formation mechanism. Refinements to our original CASSOWARY data using the Hubble Space Telescope allowed us to disentangle complex merging environments at the centers of these eight progenitors, which further solidified the notion that progenitors are indeed transitioning toward fossil systems.
DEDICATION

This work is dedicated to my incredibly loving and patient wife, my family who unwaveringly supported my decision to pursue this dream, and my father who has guided me the entire way. Words cannot express the love I have for you all. Thank you.
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I would like to thank Jimmy Irwin for his exceptional role as advisor and mentor to me throughout my research career. His careful guidance taught me how to ask meaningful questions about the universe and how to go about finding the answers. I thank William Keel for offering to pass on his expertise in the intricacies of observing which proved to be a valuable tool (and for all the interesting and entertaining stories of mishaps in observing he was willing to share). I am grateful to Raymond White, Jeremy Bailin, Ming Sun, and Marcos Santander for agreeing to be a part of this committee; their constructive criticism was beneficial and this work is better for it. I also would like to thank NASA who supported my research through their grants and use of their instruments.
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CHAPTER 1

INTRODUCTION

Galaxy groups and clusters are among the most massive gravitationally bound structures in the universe as well as some of the oldest. As baryons in the early universe fell into the gravitational potential wells of dark matter halos, gas was able to cool, condense, form stars, and coalesce into what we know as galaxies and collections of galaxies. The most massive galaxy inside a given halo is expected to sink to the center of the potential and grow via merging with other galaxies, forming what is known as the brightest cluster galaxy (BCG) or brightest group galaxy (BGG) depending on the total size of the system with clusters being considered richer environments than groups. Over time, dynamical friction can cause other intermediate mass galaxies near the BCG/BGG to lose angular momentum and fall inwards to be cannibalized by the central galaxy thereby growing it further. The properties of this BCG/BGG can hold information about the entire galaxy system and is a popular research topic in astrophysics, as these are products of both initial system conditions and complex interactions with other galaxies over the lifetime of the system. Additionally, much gas is pulled into the system’s potential that is not incorporated into galaxies. This forms a halo of heated gas known as the intracluster medium (ICM) which can be observed in X-rays and also holds much information about the systems as a whole.

The majority of BCG/BGGs have been observed to outshine fellow member galaxies in magnitude space by anywhere from $0.5 < m < 1.5$, however a small subset of systems show a BCG/BGG magnitude difference of over 2.0 between the first and second rank galaxy ($\Delta m_{12} > 2.0$) within half the system’s radius. These over-luminous central galaxies also seem
to be accompanied by a deficit in intermediate mass galaxies when compared against groups
with more average sized central galaxies. This led Jones et al. (2003) to formally define these
interesting galaxy systems as fossil systems. They reasoned that in order for such a large
BCG/BGG to exist, it must have taken an extremely long time to form thus making these
systems much older than systems with smaller BCG/BGGs. Further study showed that these
fossil systems seem to exhibit more cluster-like tendencies in their ICMs than poorer groups,
especially when comparing against systems with comparable numbers of member galaxies.
This led many to conclude that fossil BGGs formed via the cannibalization of nearly all the
intermediate mass member galaxies within half the system’s radius; such a scenario explains
both the existence of a dominant central galaxy and the deficit of intermediate mass galaxies
seen in fossils.

The picture was soon complicated by results from N-body simulations which showed
fossil systems both being formed and destroyed over cosmic time (von Benda-Beckmann
et al. 2008), suggesting that perhaps fossil systems are not an evolutionary end but an
evolutionary phase that all systems have a chance of passing through. If this were the case,
one could expect to find galaxy systems in the process of becoming fossil systems if one knew
where to look. Most fossil systems found to date lie within \( z < 0.2 \), meaning that if one were
to look at higher redshifts, one could find the progenitors to today’s fossil systems not in
simulations but in surveys. This thought crystalized with the discovery of the Cheshire Cat
fossil progenitor system by Irwin et al. (2015). The Cheshire Cat galaxy group \( (z = 0.43) \)
was first identified by Belokurov et al. (2009) in the CAmbridge Sloan Survey of Wide ARcs
in the Sky (CASSOWARY) catalog, as it is a spectacular strong lensing system formed by
a relatively poor group. Irwin et al. (2015) found that the system was in fact an ongoing
group merger in which the two BGGs that once belonged to separate groups are orbiting
one another at the new group center and are predicted to merge within 0.9 Gyr. While
individually the two BGGs are not bright enough to constitute a fossil system, the new
merged BGG will be, and since this is expected to occur within the group’s look back time

2
of 4.5 Gyr, the Cheshire Cat strong lensing system can be classified as a progenitor to today’s fossil systems.

The discovery of a fossil progenitor that also happens to be acting as a strong gravitational lens led us to wonder if there were some connection between the two. This motivated us to investigate the rest of the CASSOWARY catalog members to see if any of these also happen to be fossil progenitors. Our publication in the Astrophysical Journal in April of 2018 involves this study and comprises Chapter 2 of this dissertation. In it, we successfully identify a number of fossils and fossil progenitors and identify a strong lensing bias where lensing systems are more likely to be fossils than similar non-lensing systems.

After the success of identifying additional fossil progenitors, we shifted our focus from optical wavelengths to X-rays. The Cheshire Cat fossil progenitor was observed by Chandra and revealed that this system had an elevated gas temperature and luminosity than one would expect from a group its size. This is believed to be due to a line of sight group merger where the gas is being shock heated. Spectroscopic redshifts of all nearby galaxies obtained from the Gemini observatory confirm this by showing a clear bimodality in redshift space with each peak resting at the redshift of each previously separate BGG. Since no other known fossil progenitors had been studied in X-rays, we requested and were awarded joint Chandra and multi-wavelength Hubble Space Telescope (HST) snapshots of eight CASSOWARY fossil progenitors at varying stages in their fossil evolution. We wished to see if there were any links between a progenitor’s evolutionary stage and its X-ray properties and if there were any other instances of our progenitors utilizing the group merger fossil formation mechanism. Additionally, the high resolution offered by HST allows us to disentangle the complex merging environments seen in ground-based images to better determine exactly what galaxies go into assembling a fossil BGG.

Chapter 3 shows our results in the X-ray regime as well as refinements to galaxy luminosity functions offered via new HST observations using galaxy fitting software designed to find the properties of overlapping or merging galaxies. Chapter 4 outlines the ongoing and
future research goals associated with this topic including new *Chandra* and *XMM-Newton* observing proposals designed to allow us to confidently compare fossils, progenitors, and non-fossils at this epoch of cosmic time \((0.3 < z < 0.6)\) and fully account for any strong lensing bias in X-ray emission so that we can accurately compare our results against others in the field. Chapter 5 summarizes all our findings for this work.
2.1 ABSTRACT

Fossil galaxy systems are classically thought to be the end result of galaxy group/cluster evolution, as galaxies experiencing dynamical friction sink to the center of the group potential and merge into a single, giant elliptical that dominates the rest of the members in both mass and luminosity. Most fossil systems discovered lie within \( z < 0.2 \), which leads to the question: what were these systems’ progenitors? Such progenitors are expected to have imminent or ongoing major merging near the brightest group galaxy (BGG) that, when concluded, will meet the fossil criteria within the look forward time. Since strong gravitational lensing preferentially selects groups merging along the line of sight, or systems with a high mass concentration like fossil systems, we searched the CASSOWARY survey of strong lensing events with the goal of determining if lensing systems have any predisposition to being fossil systems or progenitors. We find that \( \sim 13\% \) of lensing groups are identified as traditional fossils while only \( \sim 3\% \) of non-lensing control groups are. We also find that \( \sim 23\% \) of lensing systems are traditional fossil progenitors compared to \( \sim 17\% \) for the control sample. Our findings show that strong lensing systems are more likely to be fossil/pre-fossil systems than comparable non-lensing systems. Cumulative galaxy luminosity functions of the lensing and
non-lensing groups also indicate a possible, fundamental difference between strong lensing and non-lensing systems’ galaxy populations with lensing systems housing a greater number of bright galaxies even in the outskirts of groups.

2.2 INTRODUCTION

Fossil systems are classically thought to be representative of old, undisturbed galaxy systems where almost all $L^*$ members have been cannibalized by the dominant central elliptical, as dynamical friction draws the massive $L^*$ member galaxies to the center over long time scales. As the central elliptical cannibalizes more galaxies, the magnitude gap between the central elliptical and the next most massive member widens and mass becomes more concentrated at the center until a ‘fossil system’ is created (Jones et al. 2003). One study of the mass concentration of fossil groups using N-body simulations show some support for this assumption toward fossil systems formation (Khosroshahi et al. 2007). Due to the apparent evolved nature of fossil systems and high concentration parameters (Wechsler et al. 2002), it is possible that studying fossil systems can help us understand properties of the early universe as well as brightest cluster/group galaxy formation. However, exactly how common fossil systems are in the universe is not well constrained.

Jones et al. (2003) originally defined a fossil system to be a galaxy group or cluster with a massive brightest group or cluster galaxy (BGG or BCG) that dominates (by more than two magnitudes in the $r$-band) the rest of the galaxies within $0.5 R_{200}$, defined as half of the virial radius of the system, and shows a bolometric X-ray luminosity $L_{X,bol} \geq 10^{42} h^{-1}_{50}$ ergs s$^{-1}$. This definition has done well in identifying massive fossil systems but has the potential to miss poorer fossil groups along with being less robust for these poor fossil groups (Dariush et al. 2010), since the infall of a lone luminous galaxy would destroy the system’s fossil status. To address this, Dariush et al. (2010) proposed altering the classic Jones optical criteria: instead of using $(\Delta m_{12} \geq 2.0)$, where $\Delta m_{12}$ is the $r$-band magnitude gap between the first
and second rank galaxies, Dariush et al. (2010) requires ($\Delta m_{14} > 2.5$), where $\Delta m_{14}$ is the $r$-band magnitude gap between the first and fourth rank galaxies. This change would allow for the infall of one or two luminous galaxies without destroying the fossil status of the poorer group. Jones et al. (2003) found that fossil systems should comprise between 8% and 20% of all galaxy groups. However, this study was only done for nearby groups and clusters of $z < 0.25$. A more recent study by Gozaliasl et al. (2014) shows that the fossil group fraction for massive galaxy groups ($M_{200} \sim 10^{13.5} M_\odot$), where $M_{200}$ is the mass within a sphere of density equal to 200 times the critical density of the universe, is $22 \pm 6\%$ for $z \leq 0.6$ and $13 \pm 7\%$ for $0.6 < z < 1.2$ if a $\Delta m_{12} \geq 1.7$ is required.

Since most fossil systems found to date lie within $z < 0.2$, fossil galaxy groups could be old, undisturbed systems, as the infall of any bright galaxy has the potential to destroy their fossil statuses. The Millennium Simulation supports this idea, as it shows fossils being formed near $z = 0.9$ and subsequently being destroyed due to the infall of a bright $L^*$ galaxy which breaks the $r$-band magnitude gap requirement before $z = 0$ (von Benda-Beckmann et al. 2008). However, as some fossils are destroyed in the simulation, others are created as bright members are consumed by the BGG (Ponman et al. 1994) thus establishing the required $r$-band magnitude gap. This result from the simulation suggests that fossil systems could be more of a ‘fossil phase’ that all groups have a likelihood of passing through as opposed to a unique class of object all their own. There also exists controversial evidence that fossils have a higher than expected mass concentration parameter (Sun et al. 2004; Khosroshahi et al. 2004, 2006), although some observations of nearby fossils dispute this (Sun et al. 2009). These pieces of evidence point to fossil systems possibly having different initial conditions than most groups. To further complicate the matter, there are many supposedly old, evolved nearby fossil systems that do not possess cool cores as would be expected from relaxed systems (Sun et al. 2004; Khosroshahi et al. 2004, 2006). These fossil systems needed an energetic event of some kind (such as an AGN turning on, a burst of star formation, or a group merger) in their recent past to heat up their intragalactic
medium (IGM) or destroy any pre-existing cool cores which is at odds with these fossils being relaxed. However, Trevisan et al. (2017) found that star formation histories of nearby fossil BGGs suggested that they grew over time via dry mergers decreasing the likelihood that star formation alone could combat IGM cooling in the supposedly dense cores of fossils.

Despite the certain existence of fossil progenitors, little observational work has gone into locating any. A progenitor to today’s fossil systems would be a system at a higher redshift with ongoing or imminent major merging, in mid-assembly of the eventual fossil system’s massive BGG\(^1\). The amount of merging concluded by \(z = 0\) would be sufficient to push the final BGG \(r\)-band magnitude two magnitudes brighter than any other remaining galaxy member within \(0.5R_{200}\). The progenitor could also be more centrally mass concentrated than other non-fossil groups at similar redshifts if fossil systems are a unique set of galaxy groups as some suggest. We expect fossil progenitors to be distinctly different from compact groups, since compact groups do not show velocity dispersions indicative of a deep cluster-like potential well, and the formation of fossil systems is not explained by the merger of galaxies in compact groups (La Barbera et al. 2010). Additionally, N-body simulations from \(0 < z < 0.5\) show that a minority of compact groups become fossils given that the mean merger time scales of \(\sim 10\) Gyr for these systems are too great to achieve a \(\Delta m_{12} \geq 2.0\) by \(z = 0\) (Farhang et al. 2017).

An overarching question in the study of fossil systems is what these groups looked like in the early universe. Are they all old, evolved systems, the inevitable end for all clusters, or are fossils simply a phase that all groups have a probability of transitioning through? While the former explanation is possible, the likelihood that the entire fossil population is comprised of isolated, undisturbed groups seems low based on the frequency of mergers in the early universe as seen in simulations. Studies of the Millennium Simulation also cast doubt on this being the sole explanation. Many fossil systems in the simulation form

\(^1\)It is important to note that it is logically possible for a BGG/BCG to be extremely efficient at turning gas into stars, essentially preventing any other large galaxies from forming in the group/cluster. Fossil systems formed via this channel would simply be “born that way,” however our data cannot distinguish between this process and early dry mergers.
between $0.3 < z < 0.6$, and the fossil system BGGs were always larger than their non-fossil counterparts (Kanagusuku et al. 2016), suggesting that fossil systems could begin with different initial conditions than most galaxy systems. By studying the Cheshire Cat fossil progenitor system, it has been demonstrated that if two groups merge, the final product has the potential to be a fossil group once the BGGs of the respective groups merge (Irwin et al. 2015). It was estimated that the first and second rank galaxies in the Cheshire Cat gravitational lens will merge in 0.9 Gyr, and once this merger concludes, the group will become a fossil system. Further, optical and X-ray observations revealed that the system is comprised of two separate galaxy groups undergoing a line of sight merger, opening another avenue for fossil system formation: (fossil) group mergers. This second possible formation mechanism offers an explanation for observed non-cool core fossil systems (as X-ray cooling time scales are typically longer than galaxy merger time scales.)

It is known that fossil systems house massive BGGs at their centers (Jones et al. 2003), implying a higher than average mass concentration when compared to normal groups of similar richness. This enhancement could make fossil-like systems more efficient strong gravitational lenses. Since gravitational lensing also preferentially selects merging systems along the line of sight, it follows that targeting systems with strong gravitational arcs nearby could be a more efficient way of locating fossil systems and their progenitors. Kanagusuku et al. (2015) found that in the Millennium Simulation, most of today’s fossils became fossils between $0.3 < z < 0.6$ which happens to be the optimal distance to observe groups that act as strong lenses (Trentham 1995). This motivates us to select our sample from the CAmbridge Sloan Survey of Wide ARcs in the Sky (CASSOWARY) catalog (Belokurov et al. 2009, Stark et al. 2013) which searches for strong gravitational arcs in the Sloan Digital Sky Survey (SDSS) and has an average lens redshift of $z \sim 0.4$. Our goals in this study are to identify more examples of fossil progenitors (such as the Cheshire Cat) in the CASSOWARY catalog using SDSS photometry, form a catalog of these progenitors, and contrast their properties against fossil and non-fossil systems. A control set of near-identical, non-
lensing galaxy groups will also be analyzed to see if the presence of a strong gravitational arc near a group biases it toward being a fossil system. We present results from our analysis of all 58 CASSOWARY members along with average cumulative luminosity functions for each category (fossil, progenitor, and normal systems).

In Section 2, we discuss the selection criteria for our sample from the SDSS archive, group scaling relations involved in determining each group’s physical parameters, how fossil status is determined, and how average luminosity functions were generated. Section 3 presents our catalog of lensing fossil systems and potential fossil progenitor systems and compares the results against a control sample of near identical, non-lensing galaxy groups. In Section 4, we propose a possible fossil system formation timeline using data from SDSS, incorporating fossil progenitors at varying stages of BCG/BGG formation. Section 5 summarizes our findings. We adopt the standard $\Lambda$CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_M = 0.286$ throughout this work.

2.3 SLOAN DATA ANALYSIS

2.3.1 Selection Criteria

The CASSOWARY catalog (Belokurov et al. 2009, Stark et al. 2013) identified strong gravitational arcs in the SDSS DR7 archive by searching for blue companions or arcs separated from a luminous red galaxy by $\sim 3''$. To date, 58 lensing systems have been identified with many having been confirmed via spectroscopic observations of both the lensing and lensed galaxies with typical lensing galaxies lying between $0.2 < z < 0.7$ and lensed galaxies beyond $z \sim 1.5$. While it was not required that the lens be a galaxy group, it was found that most were. Moreover, many of the CASSOWARY groups were not previously identified in group catalogs, as they generally have few members and their higher redshifts create difficulties for automated selection techniques.

Our analysis primarily used SDSS DR12 photometric data, which consists of over 100 million cataloged sources observed in the $ugriz$ bands that span over a quarter of the sky.
Unfortunately, due to the vastness of the data set, only the brightest galaxies have available spectra, limiting our ability to know precise distances and therefore accurate group membership. We therefore use photometric redshift (photoZ) estimates provided in the SDSS archive which are found using the observed colors of the sources and correlate them to a database of spectroscopic redshifts (specZ) of galaxies of similar colors. This method allows for an estimate of the source’s distance, bearing in mind that improvements could be made once a spectrum is taken.

It is important to note where the uncertainties in SDSS’s photoZ measures come from and how they can be minimized. The error in the photoZ estimate directly correlates with the errors in the source’s colors, meaning the fainter sources have less accurate corresponding photoZ. Normally, at the distances of our targets, solely relying on photoZ to determine group membership is not optimal, so we developed a technique to construct reliable photoZ cuts for the other groups without spectroscopic information. *Gemini* GMOS optical spectroscopic redshifts for 48 galaxies for the Cheshire Cat (also a CASSOWARY object known as CSWA 2) were available (Irwin et al. 2015) along with supplemental redshifts found in the literature; these allowed us to confidently determine group membership. We therefore chose to use this group to construct our photometric inclusion criteria for the other CASSOWARY catalog systems. By querying SDSS for all available photoZs of each confirmed member of CSWA 2 along with their errors (18 were too faint for SDSS to estimate any photoZ) and comparing them to each specZ, we determined that a $2\sigma$ inclusion window about the BGG’s specZ was sufficient to include all
but the dimmest members (Figure 2.1).

In order to count red-sequence (or red-ridge) elliptical galaxies for use in group scaling relations, we incorporate a series of color cuts to exclude blue, late-type galaxies as well as any red-ridge ellipticals at the wrong redshift. The average redshift of the CASSOWARY groups, combined with most CASSOWARY member galaxies being red-ridge ellipticals, drove us to omit the $u$-band; the SDSS $u$-band errors were large for even the brightest BGG in our sample suggesting that including the $u$-band would add little information to our analysis. Thus, every color combination using the $griz$ bands was inspected for the confirmed Cheshire Cat member galaxies. The tightest groupings would limit the number of interlopers being accidentally counted among the red-ridge elliptical members (Figure 2.2). Four parallelograms in color-color space were chosen and are displayed in Table 2.1. Galaxies outside any parallelogram are excluded. These two criteria were used to determine group membership status for the rest of the CASSOWARY catalog. The lack of spectra for each group means that when using these cuts the results will not be pure, however statistically they are complete.

### Table 2.1: Equations for lines used to build parallelograms in color space to exclude all galaxies except red-ridge ellipticals useful for group scaling relations with each inclusion region denoted by R1, R2, R3, and R4. K-corrections and stellar evolutionary corrections are included to bring galaxies to a $z = 0$ frame.

<table>
<thead>
<tr>
<th>Cut 1</th>
<th>Cut 2</th>
<th>Cut 3</th>
<th>Cut 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(g - z) &gt; -3.63(g - r) + 3.0$</td>
<td>$(g - z) &lt; 1.05(g - r) + 1.11$</td>
<td>$(g - z) &lt; -3.63(g - r) + 7.45$</td>
<td>$(g - z) &gt; 1.05(g - r) + 0.35$</td>
</tr>
<tr>
<td>$(r - i) &gt; -0.25(g - i) + 0.28$</td>
<td>$(r - i) &lt; 0.81(g - i) - 0.29$</td>
<td>$(r - i) &lt; -0.25(g - i) + 1.23$</td>
<td>$(r - i) &gt; 0.81(g - i) - 1.04$</td>
</tr>
<tr>
<td>$(i - z) &gt; -0.94(r - i) + 0.20$</td>
<td>$(i - z) &lt; 1.95(r - i) + 0.25$</td>
<td>$(i - z) &lt; -0.94(r - i) + 1.05$</td>
<td>$(i - z) &gt; 1.95(r - i) - 1.73$</td>
</tr>
<tr>
<td>$(r - z) &gt; -0.41(g - i) + 0.63$</td>
<td>$(r - z) &lt; 0.90(g - i) + 0.93$</td>
<td>$(r - z) &lt; -0.41(g - i) + 1.73$</td>
<td>$(r - z) &gt; 0.90(g - i) - 1.18$</td>
</tr>
</tbody>
</table>

Figure 2.2: The four color-color group inclusion parallelograms created for the Cheshire Cat (CSWA 2) for red-ridge ellipticals; K-corrections and stellar evolutionary corrections have been included. Red triangles show confirmed member galaxies and black circles show interlopers. Error bars were calculated quadratically from the reported SDSS DR12 magnitude errors. Confirmed member galaxies outside the regions are very faint and were only confirmed via spectroscopic redshifts.
To account for the relatively high redshift of the CASSOWARY groups, K-corrections for groups of $z < 0.5$ were found using the “K-corrections Calculator” (Chilingarian et al. 2010)$^2$. For groups with $z > 0.5$, K-corrections were estimated using $D_n4000$ measures (Westra et al. 2010) assuming a typical elliptical galaxy $D_n4000 \sim 1.65$. Stellar evolutionary corrections for the $griz$ bands were taken from Roche et al. (2009). Finally, we imposed a corrected $i$-band magnitude limit of $m_i < 20.84$ to find $N_{200}$, defined as the number of red-ridge ellipticals with $L_{gal} > 0.4L^*$ inside the group’s virial radius, taken to be $R_{200}$ (Wiesner et al. 2012).

In order to find each group’s $R_{200}$ and other physical properties, we adopted an iterative process using group scaling relations involving $N_{200}$ in Lopes et al. (2009),

$$\ln(R_{200}) = 0.05 + 0.39\ln\left(\frac{N_{200}}{25}\right)h^{-1}_{70} \text{ Mpc}$$ (2.1)

$$\ln(M_{200}) = 0.21 + 0.83\ln\left(\frac{N_{200}}{25}\right)h^{-1}_{70} \text{ M}_\odot$$ (2.2)

We first adopted a characteristic $R_{200}$ of 1 Mpc as a starting point. This size was used in an SDSS query to extract all galaxies within the circular angular region. These galaxies were analyzed using our color/photoZ selection criteria which gave us a preliminary value for that system’s $N_{200}$. To deal with any remaining interlopers present within the extraction region, which could slightly inflate $N_{200}$ and consequently $R_{200}$, we took eight regions of angular size equal to the group’s current $R_{200}$ immediately adjacent to the target group and applied the same selection process to the galaxies within these regions. We averaged these eight results together to obtain an expected $N_{200}^{interloper}$ for each group based on the group’s location in the sky. This value was subtracted from the group’s $N_{200}$ to arrive at a more accurate richness. The new $N_{200}$ was used to calculate a new $R_{200}$, and the process was repeated until a single value for $N_{200}$ and $R_{200}$ was converged upon. By using this method, we were able to agree with other SDSS galaxy cluster richness catalogs (Wen et al. 2012) on $N_{200}$ to within 10%.

$^2$http://kcor.sai.msu.ru/
for the 17 groups with existing $N_{200}$ estimates. Errors in galaxy colors were dealt with by adding in quadrature, and if a galaxy’s color error bars pushed it into the inclusion regions, it was counted as a potential group member; this only significantly changes results in the most distant groups.

### 2.3.2 Determining Fossil Status

With color cuts, photometric redshift cuts, galaxy interloper averages, and reliable $R_{200}$ estimates in hand, we constructed galaxy membership catalogs for all 58 CASSOWARY members. At this point, we checked the fossil status of each group using both the Jones et al. (2003) criteria of $\Delta m_{12} \geq 2.0$ and the Dariush et al. (2010) criteria of $\Delta m_{14} \geq 2.5$; systems which satisfied the optical criteria as-is were labeled as fossil systems. Groups which were not classified fossil systems moved on to the next stage of analysis to determine whether they are fossil progenitors.

Taking the brightest galaxy as the center of the system, we calculated the projected separation of all members from the BGG along with their masses (assuming a mass-to-light ratio of six in the $r$-band). We took this information and calculated an expected time scale for the galaxy to merge with the BGG for each member using $T_{\text{merge}} \approx 1.6 r M_\star^{-0.3}$ Gyr, where $r$ is the maximum projected separation of the galaxies in units of $35.7 h_{0.7}^{-1}$ kpc and $M_\star$ is the sum of the galaxies’ masses in units of $4.3 \times 10^{11} h_{0.7}^{-1} M_\odot$ (Kitzbichler & White 2008). We adopt this time scale since it likely overpredicts the merger time by a factor of two relative to other methods (Kitzbichler & White 2008) ensuring the merger is most likely completed in the specified time scale. Based on the group’s look back time, we determined which member galaxies had sufficient time to be cannibalized by the BGG and their luminosities added to the BGG. Using this ‘new’ BGG luminosity, the fossil status of each group was again checked; if a group became a fossil via this process it was labeled as a fossil progenitor. Finally, all groups that still did not meet either fossil criteria were labeled for this work as normal groups, as no amount of possible merging could build a large enough BGG for these groups to transition into fossil groups by $z = 0$ (Table 2.2).
2.3.3 Luminosity Functions

Once all 58 CASSOWARY catalog members were sorted based on their fossil status, we converted galaxy apparent $r$-band magnitudes ($m_r$) into absolute magnitudes ($M_r$) using

$$M_r = m_r - 25 - 5\log\left(\frac{D_L}{1\text{ Mpc}}\right) - K_r - 0.85z$$

(2.3)

where $D_L$ is the luminosity distance to the group, $K_r$ is the $r$-band K-correction, and the last term is the stellar evolutionary correction involving the group’s redshift (Roche et al. 2009).

We then generated three average luminosity functions (one for fossils, one for progenitors, and one for normal groups) using all the member galaxies for each category. Due to the low galaxy count in the brightest bins of the average luminosity functions, errors in galaxy count were handled using Poisson statistics with $\sigma \approx 1 + (n + 0.75)^{1/2}$ where $n$ is the number of member galaxies within the luminosity bin (Gehrels 1986).

2.4 DISCUSSION

2.4.1 CASSOWARY Strong Lensing Sample

Of the 58 CASSOWARY members, it was found that six are most likely large, lone ellipticals (possessing an $N_{200} < 5$) that happen to act as strong gravitational lenses and were not included in any luminosity functions or fossil/progenitor fractions. Of the remaining 52 strong lensing systems, we found that $13.5 \pm 2.8\%$ are Jones fossils ($\Delta m_{12} \geq 2.0$) and $17.3 \pm 2.6\%$ are Dariush fossils ($\Delta m_{14} \geq 2.5$), consistent with the expected 8% to 20% fossil system rate for randomly selected groups within $z < 0.2$ (Jones et al. 2003). We found that $23.1 \pm 2.5\%$ of the CASSOWARY systems are Jones fossil progenitors and $28.9 \pm 2.5\%$ are Dariush fossil progenitors. This higher rate of fossil progenitors in the CASSOWARY sample is not surprising considering that Kanagusuku et al. (2016) found that in the Millennium Simulation, systems which were fossils at $z = 0$ finished forming their BGG (creating the

\[^3\text{Errors are reported at 1}\sigma\text{ confidence.}\]
required $\Delta m_{12}/\Delta m_{14}$ r-band magnitude gap) between $0.3 < z < 0.6$ on average. Since the average redshift of the CASSOWARY members is $z \sim 0.4$, we expect to see a collection of near-fossil systems, as we are seeing analogs to today’s fossil systems in mid-cannibalization of their $L^*$ members. An interesting thing to note is that if one assumes all the CASSOWARY progenitors and fossils become/stay fossils, one arrives at a $z = 0$ Jones fossil percentage of $36.6 \pm 2.4\%$ and a Dariush percentage of $46.1 \pm 2.3\%$; this implies we should see far more nearby fossil systems than we currently do. One explanation why we do not see such an overabundance of nearby fossils is that fossils are transitory in nature, and the look back time is long enough to allow some bright galaxies to fall within half of the fossil’s virial radius thereby breaking the fossil’s status. Another explanation is that in the CASSOWARY strong lensing sample, we are seeing a subset of systems that are more likely to be fossil systems; these two hypotheses will be explored further in the non-lensing control sample section.

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<th>Dec (BGG)</th>
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<th>$D_{eff}^{BGG} (\text{kpc})$</th>
<th>$N_{200}$</th>
<th>$M_{200} \times 10^{14} M_\odot$</th>
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To better determine if we are truly seeing the progenitors of today’s fossil systems, we contrasted the galaxy luminosity functions of each category against one another, as fossil system luminosity functions show a clear deficit in $L^*$ members when compared to comparable sized normal groups and clusters (Gozaliasl et al. 2014). Fossil progenitors might be expected to be a transitional step between the two extremes, losing $L^*$ galaxies as they are consumed by the BCG’s. We created three average cumulative galaxy luminosity functions (a fossil, progenitor, and normal function) from the CASSOWARY lensing sample to ensure we were comparing strong lensing systems to other strong lensing systems$^4$. Due to the large amount

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$^4$In the cases of split identification (e.g., Jones fossil and Dariush progenitor), the Jones criterion was chosen for forming the luminosity functions since it is the most widely cited.

### Table 2.2: All 58 CASSOWARY members and their general properties with $D_{\text{off}}^{BGG}$ indicating the BGG offset from the lensing center of mass. Since both Jones et al. (2003) and Dariush et al. (2010) criteria were used to determine fossil status, we include the magnitude gap in the $r$-band between the first and second rank galaxy ($\Delta m_{12}$) along with the first and fourth rank galaxy ($\Delta m_{14}$) within $0.5R_{200}$. The $P_{J/D}$ and $F_{J/D}$ columns were added to differentiate between Jones(J)/Dariush(D) progenitors or fossils, respectively. Bolded entries indicate optical fossil status being reached either now or after merging is completed. Dashes under the merged column indicate all galaxies within $0.5R_{200}$ merging into one BGG by $z = 0$. $t_{\text{merge}}$ indicates the expected merger time scale from Kitzbichler & White’s (2008) relation until fossil status is achieved. * Double nucleus detected in archival HST imaging negating fossil status until merging is finished. ⋄ The geometry of CSWA 36 prevents the arc from being easily fit and thus no offset was measured. † No spectra available for source galaxy; lensing confirmation needed. ‡ Gemini GMOS data from Grillo et al. (2013).

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&emsp;2.8

$^*$ Double nucleus detected in archival HST imaging negating fossil status until merging is finished. ⋄ The geometry of CSWA 36 prevents the arc from being easily fit and thus no offset was measured. † No spectra available for source galaxy; lensing confirmation needed. ‡ Gemini GMOS data from Grillo et al. (2013).
Figure 2.3: Left: Cumulative luminosity functions of CASSOWARY systems separated by classification: normal, progenitor, and fossil. The curves represent the best fit Schechter function found using least squares fitting for each population excluding the BGGs. The progenitor function falls between the normal and fossil functions at the bright end ($L \gtrsim 10^{11} L_\odot$), supporting the idea that fossil progenitors are a bridge between normal and fossil systems. Right: The same luminosity functions binned by inner and outer half virial radii. The inner regions exaggerate differences between the three populations which may be due to frequent mergers/interactions of members. The outer regions show little statistical difference from one another, however as a whole, the outer members possess more bright galaxies than the best-fit model would suggest. Error bars are at 1σ.

of overlap between the two prevailing fossil criteria (Jones/Dariush) in this sample, the cumulative luminosity functions combined both Jones and Dariush fossils/progenitors to minimize errors. It is important to note that the poor fitting at the bright end is due to the “BCG bump,” a known artifact of galaxy mergers in the centers of clusters and groups (Hansen et al. 2005). Excluding the BGGs, we found that overall, the lensing fossil and normal population fits are nearly identical. However, when the BGGs are introduced into the data set, we found that the fossil luminosity function greatly diverged from the normal luminosity function at the bright end, as expected (Figure 2.3). The progenitor luminosity function matched the normal function at the faint end. However, the progenitor function fell between the normal and fossil functions at the bright end suggesting that fossil progenitors are currently losing their intermediate members while gaining very bright members, thereby moving the groups closer to fossil status. This supports the notion that fossil systems form their massive BCGs via cannibalization of intermediate mass member galaxies. SDSS images
of the inner regions of groups classified as fossil progenitors also very often show an extremely crowded environment near the BCG further supporting this mechanism of fossil formation (Figure 6).

We also find that while many CASSOWARY systems visually appear to be compact groups, none reach the compactness criteria of a $\mu_G < 26.0$ surface brightness in the smallest circle that includes at least three galaxies within three magnitudes of the BGG (Hickson 1982) making none of our systems compact groups. This supports the findings of Farhang et al. (2017) in the Millennium Simulation where only $3 \pm 2\%$ of fossil systems were simultaneously compact groups. The fact that none of the 12 Jones progenitors in our $0.2 < z < 0.7$ sample were compact groups contrasts their estimates of $36 \pm 2\%$ of fossil progenitors being identified as a compact group between $0 < z < 1.0$. We hesitate to place our own numerical constraints on this fraction, as our sample varies greatly from theirs and we believe is not large enough to show any meaningful correlations on its own.

Much work has been done investigating the global deficit in intermediate-luminosity members and the value/evolution of the faint-end slope of the fossil luminosity function, finding that the deficit in $L^*$ members is likely due to cannibalization by the BCG and the faint end slope is consistent with normal groups (Lieder et al. 2013, Gozaliasl et al. 2014, Zarattini et al. 2015). However, little work has gone toward investigating fossil populations in different radial bins, where initial group conditions could still be encoded (particularly in the outer regions). Binning the average luminosity functions into inner ($r \leq 0.5R_{200}$) and outer ($0.5R_{200} < r \leq R_{200}$) regions reveals that this deficit in intermediate mass galaxies/abundance of extremely bright galaxies in fossil progenitors and fossil systems is exaggerated for $r \leq 0.5R_{200}$ (Figure 2.3; right). This is likely due to the increased galaxy density near the center effectively speeding up the galaxy interaction rate, therefore the central regions of fossil or near-fossil systems should show the most extreme differences from non-fossils. While the inner progenitor fit is nearly identical to the normal fit, when the BGGs are included in the histogram a clear difference can be seen, placing it firmly between the normal and fossil
functions.

We quantified the statistical significance of these differences between datasets via a one-sided K-S test which gives the probability that differing data sets come from the same cumulative distribution function. For $0 < r \leq 0.5R_{200}$, even with the relative lack of data points, lensing fossil systems showed only a 0.84% chance of being identical to normal lensing systems. Due to a larger sample size, lensing progenitors also proved to be significantly different than normal lensing systems with only a 0.01% chance of being identical within $r \leq 0.5R_{200}$. Unfortunately, due to insufficient galaxy counts in the lensing fossil population, we were not able to find a significant difference between lensing fossils and progenitors. The outer half virial radii galaxies showed no statistically significant differences between the populations, suggesting that most differences in galaxy populations for fossil systems exist near the center where the most processing has occurred. However, all lensing systems exhibit an average $\sim 2\sigma$ deviation from a Schechter function in the outer $0.5R_{200}$ for galaxies brighter than $L^*$ which is surprising. Since these galaxies are farther away from the center, one would expect them to be much less processed and therefore be better represented by the fits. Additionally, there are no BGGs in the outer regions to skew the data away from a Schechter function. While by no means definitive, this suggests that lensing systems may form differently from non-lensing systems of comparable mass.

A consequence of the CASSOWARY systems acting as strong lenses is that we have a convenient and independent way to locate the center of mass of the inner regions of each group which can help shed light on the supposed relaxed nature of fossils. The difference between this lensing center of mass and the luminosity centroid of the BGG offers information regarding the age of the group with large offsets implying a younger system (Raouf et al. 2014). On average, we see normal, progenitor, and fossil system BGG offsets of $13.5 \pm 2.6$ kpc, $14.6 \pm 4.3$ kpc, and $7.8 \pm 2.0$ kpc respectively. Immediately apparent is the smaller offset fossils have compared to other systems; this supports the idea of fossils being more relaxed (and possibly older) than non-fossils on average. Also noticeable is the high offset and wide
spread in progenitor BGGs which could be partially explained by their disturbed nature evident in images and range of fossil transition time scales. Since the progenitor BGG offset is consistent with the normal BGG offset, one cannot say on average that progenitors are older or younger than normal systems; a case-by-case analysis would be needed.

2.4.2 Non-lensing Control Sample

All members of our sample exhibit strong gravitational arcs near the BGGs, implying a high central mass concentration for these systems. To see how/if the presence of strong gravitational arcs biases our fossil system and progenitor findings, we assembled a one-to-one random control sample of non-lensing groups from the Augmented maxBCG cluster catalog (Rykoff et al. 2012), Clusters of galaxies in SDSS-III (Wen et al. 2012), and Richness of Galaxy Clusters (Oguri 2014) catalogs. Control groups were selected to match (within 10%) each CASSOWARY group in both redshift and galaxy richness, and when multiple matches for control groups were found among the catalogs, the closest match was chosen. To increase the accuracy of this one-to-one comparison, we found two non-lensing matches for each CASSOWARY group\(^5\). To ensure that our non-lensing control sample’s halo properties matched as closely as possible to the CASSOWARY groups, we compared each control group’s stellar luminosity against its lensing counterpart’s; this can be used as a proxy for a system’s stellar mass in \(M_\star - M_{\text{halo}}\) relations. The average scatter in \(M_\star\) for a given \(M_{\text{halo}}\) is a factor of 1.4 (Behroozi et al. 2010); we measure a factor of 1.1 scatter in our sample. This means we are

\(^5\)Only one non-lensing match was able to be found for CSWA 31 and CSWA 102 due to their high redshifts (\(z = 0.683\), and \(z = 0.639\)) and poor member count (\(N_{200} = 5\)).
limited by the scatter inherent in the relation and not our sample (Figure 2.4).

Using the same photoZ and color cuts as the lensing sample, we found fossil percentages of 2.9 ± 1.6% (Jones) and 13.6 ± 1.2% (Dariush) and fossil progenitor percentages of 17.5 ± 1.2% (Jones) and 25.2 ± 1.1% (Dariush) showing that while being a strong gravitational lens does not significantly alter the Dariush fossil fraction, it does greatly improve the chances that a fossil will be a classic Jones fossil. The progenitor fraction is consistent between the control sample and lensing sample suggesting that in general the progenitor fraction is not greatly affected by the presence of gravitational arcs. We note that while the non-lensing Dariush fossil fraction is consistent with previous findings (Jones et al. 2003, Gozaliasl et al. 2014 for \( z \leq 0.6 \), and Trevisan et al. 2017), our non-lensing Jones fossil fraction of 2.9 ± 1.6% is below their estimates of 8% – 20%, 22 ± 6%, and \( \sim 10\% \) respectively. This could be partially due to the Gozaliasl et al. (2014) \( \Delta m_{12} \geq 1.7 \) criterion being less restrictive than the classical Jones et al. (2003) \( \Delta m_{12} \geq 2.0 \). However, we stress that their samples included nearby \( (z < 0.25, z \leq 0.6, \text{ and } z < 0.07) \) groups; we are probing a different epoch (upwards of 3 Gyr of available time for group evolution) by excluding the redshift range where most fossils are seen today. This combined with the knowledge that most of today’s fossils began BGG assembly between \( 0.3 < z < 0.6 \) (Kanagusuku et al. 2016) helps explain why we see fewer fully formed fossils in our control sample.

To see if the lower fossil occurrence rate in our sample could be due to inadvertently including too many bright interloper galaxies (since spectroscopic data is lacking for these groups) we calculated the bright galaxy \( (L_\odot > 0.4 L^*) \) overdensity within each CASSOWARY group compared to the surrounding regions. In non-fossil CASSOWARY groups, an overdensity of bright galaxies (sufficient to prevent that group from being a fossil) within \( 0.5 R_{200} \) was confirmed at 13σ confidence above the expected interloper value, indicating our fossil fractions are reliable. The apparent fossil deficit could be accounted for due to the redshift range of our sample \( (0.2 < z < 0.7) \). Since most fossils discovered lie near \( z \sim 0.1 \), and Kanagusuku et al. (2016) found in the Millennium Simulation that most \( z = 0 \) fossils made
the transition between $0.3 < z < 0.6$, there could be a lower fossil fraction in our samples.

Average galaxy luminosity functions were also generated for the non-lensing sample to compare against the lensing sample to see how strong lensing might affect a group’s galaxy population (Figure 2.5). The non-lensing fossil and normal luminosity functions exhibit similar behavior as the lensing sample. Non-lensing fossils show a 0.01% chance of being identical to non-lensing normal and progenitor systems, confirming that on average fossil systems’ inner regions house a different population of galaxies than non-fossils. Interestingly, non-lensing progenitors showed virtually no differences from non-lensing normal systems at any radii; this reinforces our hypothesis that the presence of a strong gravitational arc marks the most extreme examples of fossil formation at all stages. Also, the non-lensing progenitor fit falls between the other two in each radial bin. Reintroducing the BGGs maintains this in-between state for the non-lensing progenitors. Applying the K-S test to the non-lensing populations showed again that significant differences only appear within $0 < r \leq 0.5R_{200}$. 

Figure 2.5: *Left:* Cumulative luminosity functions of our non-lensing control sample for all member galaxies. For non-lensing groups, differences in the bright end (while still visually apparent) are not as prominent as our lensing systems, supporting the existence of a strong lensing bias. *Right:* The same non-lensing luminosity functions binned by inner and outer half virial radii. The inner regions for non-lensing fossils and progenitors also show the excess of bright member galaxies when compared to normal groups, though again, less pronounced than in our lensing sample. The outer regions show virtually no difference between progenitors and normal groups, with fossils only housing a few more bright galaxies. Error bars are at 1$\sigma$. 

Average galaxy luminosity functions were also generated for the non-lensing sample to compare against the lensing sample to see how strong lensing might affect a group’s galaxy population (Figure 2.5). The non-lensing fossil and normal luminosity functions exhibit similar behavior as the lensing sample. Non-lensing fossils show a 0.01% chance of being identical to non-lensing normal and progenitor systems, confirming that on average fossil systems’ inner regions house a different population of galaxies than non-fossils. Interestingly, non-lensing progenitors showed virtually no differences from non-lensing normal systems at any radii; this reinforces our hypothesis that the presence of a strong gravitational arc marks the most extreme examples of fossil formation at all stages. Also, the non-lensing progenitor fit falls between the other two in each radial bin. Reintroducing the BGGs maintains this in-between state for the non-lensing progenitors. Applying the K-S test to the non-lensing populations showed again that significant differences only appear within $0 < r \leq 0.5R_{200}$. 

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Figure 2.6: Left: Contrasting the best fit Schechter functions, excluding the BGGs, of lensing/non-lensing samples at inner-half and full virial radii bins separated by fossil status. The CSWA strong lensing fit is shown with a solid line and the non-lensing control fit is represented by the dashed line with the derived $L^*$ for each model marked. Right: Galaxy member data taken from SDSS with BGGs included. Circles represent the lensing systems, and triangles mark the non-lensing systems. In each case, lensing groups show a deficit of intermediate-luminosity members and an excess in bright members implying that lensing systems could be an example of the most extreme fossil systems along with them being more likely to become fossils as opposed to similarly sized non-lensing systems.

2.4.3 Comparing Lensing vs. Non-Lensing Samples

A comparison of the lensed vs. non-lensed fossil luminosity function revealed interesting distinctions; on average, lensing fossil systems lack intermediate mass galaxies and house larger BGGs than their non-lensing counterparts (Figure 2.6). While the latter is not terribly surprising (as larger galaxies are more likely to act as good gravitational lenses), the former offers help explaining why the lensing sample has significantly more Jones fossils than the non-lensing sample; the lensing sample is the extreme case in fossil formation. In CASSOWARY fossils (and progenitors to a lesser extent), we are seeing elevated $L^*$ cannibalization resulting in intermediate galaxy deficits and an overrepresentation of extremely bright galaxies. Comparing the non-lensing progenitor fit to its lensing counterpart reveals even sharper differences between non-lensing fossils and lensing fossils (top of Figure 2.6). On average, the lensing progenitors have fewer bright $L^*$ galaxies than the non-lensing progenitors. This could be an indication of a strong lensing selection bias. Since the presence
of strong lensing indicates a high mass concentration, lensing progenitors could have already had most of their $L^*$ members consumed by the BGGs.

Since Dariush fossils do not need such a large luminosity difference between the BGG and the next ranked galaxies, the non-lensing control sample holds many more Dariush fossils than Jones fossils. The non-lensing control sample also indicates that while the presence of a strong gravitational arc does not strongly affect the likelihood of finding the progenitors to today’s fossils around $z \sim 0.4$, it does appear to greatly increase the probability of locating Jones fossil systems. Applying the K-S test, this time to lensing vs. non-lensing systems, again shows significant differences only within $0.5 R_{200}$. For the inner regions, normal systems proved to be consistent between lensing and non-lensing systems. Progenitors, on the other hand, showed a 0.01% chance of being identical; such a striking result means that a strong lensing bias may very well exist. Since lensing progenitors on average show different galaxy populations than non-lensing progenitors, it can be inferred that the same (if not more) can be said for lensing vs. non-lensing fossils. Unfortunately, errors in bin count for both fossil populations kept us from arriving at any meaningful result; this can be remedied by increasing the sample size.

When one compares the best fit Schechter functions of lensing vs. non-lensing systems as a whole, an interesting distinction is found: at every radial bin, systems acting as strong gravitational lenses exhibit an intermediate-luminosity member deficit regardless of fossil status. While this is expected near the center of most groups, (the act of forming the BGG consumes many of these galaxies thereby shifting $L^*$ toward the faint end) this deficit supports the existence of a strong lensing bias toward fossil-like systems. To test whether or not these lensing systems are preferentially selecting systems with different initial conditions from normal groups, thereby supporting the idea that some fossils are born differently than most systems, the outer regions must be probed to see if the galaxy populations differ there as well. However the overall lack of members in the outer half virial radii of the systems made any conclusions statistically insignificant.
2.5 PROGENITOR - FOSSIL PROPERTIES, TIMELINES, AND THE LONGEVITY OF FOSSIL SYSTEMS

Since we have many progenitors in the CASSOWARY catalog with a wide range of merging time scales until transitioning into a fossil system (Table 2.2), we can form a rough timeline of today’s average fossil system’s formation process from its beginning, through the cannibalization phase building the large BGG, and finally concluding with a fossil system housing a large BGG and possessing a deficit in bright $L^*$ galaxy members. To better illustrate the hypothesis of formation of a fossil system through the progenitor phase, we have assembled a collage of SDSS images from the CASSOWARY catalog (Figure 3.4). We order them to simulate the building of a fossil BGG via cannibalization of $L^*$ members. Early in the progenitor phase, we expect there to be many bright galaxies present in the group and concentrated near the BGG, since dynamical friction has slowed the orbits of the largest galaxies and caused them to fall inward over the group’s history. As time until fossil status is achieved shortens, more and more $L^*$ galaxies will merge with the BGG subsequently shifting the galaxy luminosity function of the group toward a fainter population leaving only one or two bright galaxies near the BGG. Once the last bright member merges with the BGG, a fossil system will form housing an elongated (possibly asymmetric) BGG. As the BGG begins to relax after the final major merger it will eventually settle into a massive symmetric elliptical galaxy stereotypical of fossil systems. A follow up study of progenitors is currently being done using Chandra/HST data to better see how the hot gas evolves alongside the stellar population as a group draws closer to the fossil threshold (Johnson et al. in preparation). We expect to see a correlation between a progenitor’s X-ray properties and time until fossil status is achieved as well.

The high redshift of the CASSOWARY sample is beneficial for locating possible precursors to nearby fossil systems. However, the look back time that allows large BGGs to form also allows new galaxies to fall within $0.5R_{200}$, potentially destroying a system’s fossil status before $z = 0$. To account for this chance as conservatively as possible, we define a ‘danger
Figure 2.7: An SDSS collage of CASSOWARY systems at various stages in BGG formation, in time order from a to h. Appearing in order from upper left to bottom right along with time until fossil formation is complete: normal group (a.) CSWA 23, (b.) CSWA 10 (3.9 Gyr), (c.) CSWA 26 (2.4 Gyr), (d.) CSWA 30 (2.0 Gyr), (e.) CSWA 2 (0.9 Gyr), (f.) CSWA 11 (double nuclei; < 100 Myr), (g.) CSWA 4 (young fossil with ongoing mergers), (h.) CSWA 1 (relaxed fossil).

zone’ for each system; this zone is the maximum projected distance from which a galaxy could free-fall inside $0.5R_{200}$ within the look back time. The free-fall time is given by:

$$t_{ff} = \frac{\pi}{2} \frac{r^3}{\sqrt{2G(M + m)}}$$

where we took $r$ to be the distance from the galaxy down to $0.5R_{200}$ for the group, as this is the threshold for a member to be considered in a system’s fossil classification. In an accelerating universe, the ultimate mass of a galaxy cluster in the far future is around two times the virial mass ($M_{200}$) at $z = 0$ (Busha et al. 2005). Since the density inside the virial radius is constant by definition, the virial radius will scale as $M_{200}^{1/3}$ making the final radius $\sim 1.25$ times the current $R_{200}$. The turnaround radius (the point beyond which matter near an overdensity of a certain mass will not collapse inward but expand) is defined as $2R_{200}$, implying that the final turnaround radius will be $\sim 2.5R_{200}$ at $z = 0$. However, since our targets are at $z > 0$, their masses have grown between when we have observed them and now. Assuming a mass growth of a factor of four between then and now, that gives a $z = 0$ virial radius of $1.6R_{200}^{obs}$ and a $z = 0$ turnaround radius of $3.2R_{200}^{obs}$. For this work, we adopt
a turnaround radius of $3.0R_{200}$ and set this as the upper limit to our ‘danger zone.’ All bright galaxies within the ‘danger zone’ that passed our group inclusion criteria and were bright enough to violate either the Jones ($\Delta m_{12} \geq 2.0$) or Dariush ($\Delta m_{14} \geq 2.5$) fossil criteria were flagged. Groups with flagged galaxies within their ‘danger zone’ may still be fossil progenitors, however one cannot rule out the possibility that one or more of the flagged galaxies will eventually fall into the group potential. We found that out of the 28 strong lensing fossil/progenitor systems in the CASSOWARY catalog, only two (CSWA 26 and CSWA 159) have no nearby galaxies bright enough to endanger their eventual fossil status making these true fossil progenitors\(^7\).

In simulations, the entire lifetime of fossil systems can be chronicled by observing when and if bright galaxies fall into the group. Observationally, it is more difficult, as we do not know the proper motions of all galaxies around the group. Spectroscopic redshifts of galaxies in and near the group can constrain the radial velocities, however the tangential components remain unknown. This means we cannot know for certain which bright galaxy outside $0.5R_{200}$ will fall inwards. Therefore, the result that only $\sim 7\%$ of $0.2 < z < 0.7$ fossil/progenitor systems will stay fossils until $z = 0$ is an extremely conservative estimate. Spectra of observed fossils and progenitors at higher redshifts have the potential to increase this estimate, as some bright galaxies will undoubtedly be eliminated, being identified as either foreground or background.

### 2.6 SUMMARY

The progenitors to today’s fossil systems have been shown to exist in the universe and can be located. Kanagusuku et al. (2016) found that in the Millennium simulation most of today’s fossils finished forming their BGGs between $0.3 < z < 0.6$ which also happens to be the optimal distance to see strong gravitational lensing. The discovery of the Cheshire

\(^7\)It is interesting to note that both CSWA 26 and CSWA 159 are classified as Dariush fossils and Jones progenitors, implying that in both cases we are witnessing the formation of extremely massive BGGs compared to their respective group richesses.
Cat fossil group progenitor (CSWA 2) in the CASSOWARY catalog of strong lensing events in SDSS prompted us to analyze the remaining 57 CASSOWARY members to see if more progenitors could be located.

In this study of CASSOWARY strong lensing systems, we find fossil rates of $13.5 \pm 2.8\%$ and $17.3 \pm 2.6\%$ for the Jones et al. (2003) and Dariush et al. (2010) criteria respectively which is consistent with the expected rate of $8\% - 20\%$ of all groups being fossil systems (Jones et al. 2003). This contrasts with our non-lensing control fossil rates of $2.9 \pm 1.6\%$ and $13.6 \pm 1.2\%$ indicating the presence of a strong lensing bias toward classical (Jones) fossil formation. Our CASSOWARY progenitor rates of $23.1 \pm 2.5\%$ and $28.9 \pm 2.5\%$ (Jones and Dariush respectively) are also elevated compared to our non-lensing progenitor rates of $17.5 \pm 1.2\%$ and $25.2 \pm 1.1\%$. Average galaxy luminosity functions for each class of system (normal, progenitor, and fossil systems) confirmed that fossil progenitors fall between the normal and fossil fits, indicating the formation of the $L^*$ galaxy deficit observed in fossil systems. For the CASSOWARY sample, the progenitor luminosity function showed a slight deficit of intermediate member galaxies supporting the hypothesis that fossil BGGs are formed via cannibalization of their $L^*$ neighbors and that we are witnessing this process in some CASSOWARY fossil progenitors.

A control sample of non-lensing groups at similar redshifts, galaxy counts, and total stellar mass was compiled to compare against the CASSOWARY lensing sytems to see how the conditions leading to a strong gravitational arc near the BGG could bias the sample. It was found that while being a strong gravitational lens slightly increases the odds of a group being a fossil progenitor, it greatly increases the odds that a group will be a Jones fossil, indicating the existence of a strong lensing bias possibly linked to the initial formation of the lensing group. Comparing the cumulative galaxy luminosity functions of the non-lensing control sample to the CASSOWARY groups showed the non-lensing progenitor function agreeing more with the non-lensing normal groups rather than transitioning to the non-lensing fossil luminosity function. This could also be an indication of the strong lensing
bias preferentially selecting the most extreme examples of fossil formation (i.e., systems with the highest mass concentration, largest intermediate mass galaxy deficit, largest BGGs). Additionally, we observe lensing systems possessing an average of $2\sigma$ more bright galaxies than the best fit gives for galaxies outside $0.5R_{200}$. This is not seen in the non-lensing systems, further supporting the existence of a strong lensing bias toward classical (and possibly older) fossil-like systems.

Most fossil progenitors in this study seem to be in the process of forming a massive BGG via $L^*$ member cannibalization making these likely progenitors of the observed cool core fossil population seen today. We are engaged in further work on the topic of cool vs. non-cool core fossil progenitors using Chandra imaging of the hot gas of eight fossil progenitors in the CASSOWARY catalog at a range of stages in their evolution toward fossil status, from 100 Myr to 5 Gyr until sufficient merging has concluded to establish the required $r$-band magnitude gap. Our goal is to observe the evolution of the hot gas component of a fossil progenitor and whether or not a cool core is present as the BGG forms (Johnson et al. in preparation).

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CHAPTER 3

CHANDRA AND HST SNAPSHOTS OF FOSSIL SYSTEM PROGENITORS

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Dupke

3.1 ABSTRACT

The search for the progenitors to today’s fossil galaxy systems has been restricted to
N-body simulations until recently, where 12 fossil progenitors were identified in the CAS-
SOWARY catalog of strong lensing systems. All 12 systems lie in the predicted redshift
range for finding fossils in mid BGG assembly, and all show complex merging environments
at their centers. None of these progenitors had archival X-ray data, and many were lack-
ing high resolution optical data making precision photometry extremely difficult. Here, we
present Chandra and HST snapshots of eight of these strong lensing fossil progenitors at
varying stages of evolution. We find that our lensing progenitors exhibit higher than ex-
pected X-ray luminosities and temperatures consistent with previously observed non-lensing
fossil systems. More precise galaxy luminosity functions are generated which strengthen past
claims that progenitors are the transition phase between non-fossils and fossils. We also find
evidence suggesting that the majority of differences between fossils and non-fossils lie in their
BGGs and that fossil systems may themselves be a phase of galaxy system evolution and
not a separate class of object.
3.2 INTRODUCTION

Fossil galaxy systems are defined as galaxy systems that exhibit a lack of intermediate brightness galaxies, instead possessing one extremely large central galaxy at their centers. These fossil systems are thought to have formed these oversized brightest group galaxies (BGGs) over time as dynamical friction slowly drags bright member galaxies down to the BGG eventually merging with it. Given enough merging, a 2.0 magnitude gap in the $r$-band between the BGG and the next brightest member within half the virial radius of the system will be formed, resulting in a classical fossil system being born (Jones et al. 2003). These fossil systems were distinguished from lone, large ellipticals by requiring them to possess a hot gas halo of $L_{X,bol} \geq 10^{42} h_{50}^{-1}$ erg s$^{-1}$. Traditionally, this was thought to take a very long time to accomplish given typical angular momentum loss rates via dynamical friction, leading many to believe that fossil systems represented the oldest galaxy systems in the universe. However, this notion is contradicted by the existence of many nearby fossil systems ($z \lesssim 0.1$) that show heated gas in their cores which is inconsistent with these systems being undisturbed (Sun et al. 2004; Khosroshahi et al. 2004, 2006), since an extremely energetic event is required to heat the intracluster medium (ICM). Such an event would also need to occur in less than the expected cooling time for these systems, necessitating a recent event implying some fossils may not be as old as previously believed.

Results from N-body simulations by von Benda-Beckmann et al. (2008) supported the notion that not all fossils are old structures, as they found many instances of fossil systems being both formed and destroyed since $z < 0.9$ indicating this may be a phase of group evolution that all groups have a chance of passing into and out of. A later study by Kanagusuku et al. (2016) found in the Millennium simulation that most groups which are classified as fossils at $z = 0$ assembled their BGGs between $0.3 < z < 0.6$. These progenitors to today’s fossils would be expected to exist near this redshift space and have imminent/ongoing major merging between intermediate mass galaxies and the BGG. Perhaps coincidentally, this is also the optimal distance away from us for strong gravitational lensing to be possible (Tren-
than 1995). This led to the discovery of the Cheshire Cat strong lensing fossil progenitor (Irwin et al. 2015).

Identifying the Cheshire Cat as fossil group progenitor also sheds light on how observed non-cool core fossils might form. Irwin et al. (2015) found the merger of two separate groups could give birth to a fossil system once the BGGs merge, and the shock heating of the hot gas would initially produce a non-cool core. Since gas cooling time scales can be longer than galaxy merging time scales, one could observe a completed fossil system in a non-cool core phase if it formed via this channel. Finding the Cheshire Cat also demonstrated that the progenitors to today’s fossil systems can be found; to that point little concerted effort had gone into locating these outside simulations (Kanagusuku et al. 2016). After the Cheshire Cat’s discovery, we attempted to locate more fossil progenitors in the CAmbridge Sloan Survey of Wide ARcs in the SkY (CASSOWARY) catalog of which the Cheshire Cat (CSWA 2) was a member (Johnson et al. 2018).

Seven classical fossil systems and 12 progenitors were discovered at varying stages of formation giving us some insight into what today’s fossils looked like during the formation of their BGGs. Comparing each fossil category’s galaxy luminosity functions (fossils, progenitors, and non-fossils) show the expected differences between fossils and non-fossils and show that progenitors lie between each function demonstrating that they are indeed the transition phase between non-fossils and fossils. Also discovered was a possible bias for systems acting as strong gravitational lenses to have a higher likelihood of being identified as a classical fossil system when compared to a near identical set of non-lensing control groups. This, combined with the knowledge that centrally concentrated masses act as better gravitational lenses, suggests that some of the CASSOWARY fossils and progenitors might represent the most extreme examples of fossil systems and/or fossil system formation.

To follow up on these results, Chandra snapshots were obtained of eight of the twelve newly discovered fossil progenitors in the CASSOWARY catalog at varying stages of BGG formation with the goal of seeing how the hot gas component of a group evolves alongside
the galaxy component of a progenitor as it approaches fossil status. To aid in resolving the innermost regions where major merging is abundant, Hubble Space Telescope (HST) images in the V, R, and I filters were also obtained for four previously unobserved systems to supplement archival data. In this work, we report X-ray luminosities and global gas temperatures for eight fossil progenitor systems along with high resolution HST imaging of fossil BGGs in mid-formation, aiming to gain a more comprehensive understanding of the changes a galaxy group undergoes as the fossil BGG forms and the system concludes its transition to fossil status.

Section 2 outlines our selection criteria, data reduction, and analysis for Chandra and HST images, Section 3 contains our findings using Chandra, Section 4 our findings from HST, Section 5 highlights individual systems of interest, and Section 6 summarizes our findings. We adopt the standard ΛCDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_M = 0.286$ for all of our equations and figures.

3.3 CHANDRA ANALYSIS

3.3.1 Target Selection

In our previous work (Johnson et al. 2018), we identified 12 Jones fossil progenitors in the CASSOWARY catalog at varying stages of BGG formation. Sloan Digital Sky Survey (SDSS) images allowed us to observe how the galaxy population of a system evolves as it makes the transition to fossil status on average, with intermediate mass galaxies being cannibalized by the BGG. This leads to average galaxy luminosity functions shifting toward the faint end as the fossil transition continues, supporting findings from N-body simulations by (Khosroshahi et al. 2007). In addition to using optical light to better understand how the stellar component evolves in fossil formation, X-ray observations help us understand how the hot ICM behaves as a system transitions to a fossil which can give more information as to the recent history of the group. Of our 12 fossil progenitors, only the CSWA 2 was previously observed in X-rays (Irwin et al. 2015) severely limiting any general conclusions that could be drawn on the
morphology of fossil ICMs. Moreover, a single progenitor only provides data for a single epoch of evolution. Ideally, one would want observations of many progenitors at varying epochs of fossil formation to form an observational timeline to supplement existing simulated data. This motivated our progenitor target selection for follow up Chandra snapshot observations.

From the 13 previously identified fossil progenitors in the CASSOWARY catalog, we selected eight at different stages in fossil formation. These stages of evolution correspond to the expected galaxy merger time scales seen in Kitzbichler & White (2008) and range from 4 Gyr to only $\sim$100 Myr until fossil BGG completion. Chandra snapshot observations were taken of these eight systems to see how the hot gas component of the groups followed the stellar evolution. Additionally, aside from one progenitor which shows tentative optical evidence of being an ongoing group merger, each group has comparable richness and mass ensuring we are comparing like systems. Table 3.1 outlines all our targets along with some basic information about each group.

<table>
<thead>
<tr>
<th>Target Name</th>
<th>RA</th>
<th>Dec</th>
<th>$z_{\text{spec}}$</th>
<th>$N_{200}$</th>
<th>$M_{200}$</th>
<th>$R_{200}$ (Mpc)</th>
<th>Time Until Fossil Status (Gyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSWA 4</td>
<td>135.3432°</td>
<td>18.2423°</td>
<td>0.346</td>
<td>32</td>
<td>1.5</td>
<td>1.2</td>
<td>0.1</td>
</tr>
<tr>
<td>CSWA 10</td>
<td>339.6305°</td>
<td>13.3322°</td>
<td>0.413</td>
<td>30</td>
<td>1.4</td>
<td>1.1</td>
<td>3.9</td>
</tr>
<tr>
<td>CSWA 11</td>
<td>120.0544°</td>
<td>8.2023°</td>
<td>0.314</td>
<td>26</td>
<td>1.3</td>
<td>1.1</td>
<td>0.2</td>
</tr>
<tr>
<td>CSWA 14</td>
<td>260.9007°</td>
<td>34.1995°</td>
<td>0.442</td>
<td>18</td>
<td>0.9</td>
<td>0.9</td>
<td>3.6</td>
</tr>
<tr>
<td>CSWA 26</td>
<td>168.2944°</td>
<td>23.9443°</td>
<td>0.336</td>
<td>83</td>
<td>3.4</td>
<td>1.7</td>
<td>2.1</td>
</tr>
<tr>
<td>CSWA 28</td>
<td>205.8869°</td>
<td>41.9176°</td>
<td>0.418</td>
<td>31</td>
<td>1.5</td>
<td>1.2</td>
<td>1.6</td>
</tr>
<tr>
<td>CSWA 30</td>
<td>132.8604°</td>
<td>35.9705°</td>
<td>0.272</td>
<td>31</td>
<td>1.5</td>
<td>1.1</td>
<td>2.0</td>
</tr>
<tr>
<td>CSWA 36</td>
<td>181.8996°</td>
<td>52.9165°</td>
<td>0.266</td>
<td>26</td>
<td>1.3</td>
<td>1.1</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 3.1: A list of our targets along with some basic information about the groups. $N_{200}$ and $M_{200}$ are measures of the number of member galaxies brighter than $0.4L^*$ and mass contained within the virial radius ($R_{200}$) of the group, respectively. $N_{200}$, $M_{200}$, and fossil transition time scale is taken from our previous work Johnson et al. (2018).
3.3.2 Chandra Observations and Processing

*Chandra* ACIS-S snapshots of our eight progenitors were taken during Cycle 17. Since these were previously unobserved, expected X-ray luminosities and temperatures were found using group scaling relations involving the number of red-ridge elliptical members brighter than $0.4L^*$ in the $r$-band, represented by $N_{200}$ (Lopes et al. 2009). Accounting for redshift and galactic absorption, fluxes were derived and exposure times chosen to yield a minimum of 100 counts for each progenitor\(^1\). The data sets processed uniformly using CIAO 4.7 coupled with CALDB 4.6.9 starting with the level 1 event files following the *Chandra* data reduction threads. Bad pixel files were applied from the standard calibration library in CALDB 4.6.9.

X-ray point sources were found via `wavedetect` and verified by eye for subtraction, since our work is focused on hot gas emission for these systems. Curiously, even with our progenitors showing signs of recent and ongoing major merging, we find no active AGN of $L_X > 10^{41}$ erg s\(^{-1}\) in any of the member galaxies. Background estimates were found by choosing large regions far from group emission with all background AGN subtracted out. We chose our fitting regions to be equal to one-quarter of each group’s virial radius ($0.25R_{200}$), as the short exposure times made group emission past this point indistinguishable from the background. The tool `specextract` was utilized for spectral work within these regions, including extracting spectra and generating RMF and ARF files for each snapshot. Spectra were fit within `XSPECTv12.9` using an `apec` thermal model incorporating Galactic absorption (Dickey & Lockman 1990) for each source using `tbabs` and $\chi^2$ statistics as well as the solar abundance table from Grevesse & Sauval (1998). Energy channels were grouped so that at least 20 counts were in a single bin with bins ranging from 0.5-7.0 keV. Any counts below 0.5 keV and above 7.0 keV were ignored due to calibration uncertainties and reduced instrument sensitivity which could introduce unwanted noise.

Spectral fitting yielded expected X-ray luminosities in the 0.5-7.0 keV energy band with results given in the 0.1-2.4 keV band. Global temperatures were found via fits for each group,

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\(^1\)CSWA 26 showed a 2\(\sigma\) detection in the ROSAT All Sky Survey; this coupled with its high $N_{200}$ motivated us to increase the exposure time to yield an expected 1000 counts.
however the relatively poor counts for all but two of our snapshots meant that rough radial
temperature profiles were only able to be generated for CSWA 26 and 28. For these, the
total counts within 0.25\(R_{200}\) were divided equally into two and three concentric annuli for
CSWA 26 and CSWA 28, respectively, centered on the X-ray centroid. The emission within
these annuli was extracted and fit, with care taken to have a minimum of 400 counts in each
region. Little to no constraints were able to be placed on metal abundances, so we chose to
fix it at 40% solar for this work. Table 3.2 summarizes our findings.

<table>
<thead>
<tr>
<th>Target Name</th>
<th>Exposure Time (ksec)</th>
<th>Count Rate (cts s(^{-1}))</th>
<th>Net Counts</th>
<th>(L_X^{0.1-2.4\text{keV}}\times 10^{43}) (erg s(^{-1}))</th>
<th>(T_X(\text{keV}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSWA 4</td>
<td>7</td>
<td>0.024</td>
<td>171</td>
<td>5.3(^{+1.4}_{-1.8})</td>
<td>2.7(^{+0.7}_{-0.5})</td>
</tr>
<tr>
<td>CSWA 10</td>
<td>12</td>
<td>0.013</td>
<td>155</td>
<td>3.6(^{+3.6}_{-1.2})</td>
<td>4.7(^{+2.3}_{-1.3})</td>
</tr>
<tr>
<td>CSWA 11</td>
<td>11</td>
<td>0.029</td>
<td>322</td>
<td>3.1(^{+0.3}_{-0.8})</td>
<td>3.0(^{+0.9}_{-0.6})</td>
</tr>
<tr>
<td>CSWA 14</td>
<td>19</td>
<td>0.010</td>
<td>192</td>
<td>3.1(^{+0.9}_{-0.5})</td>
<td>3.4(^{+1.5}_{-0.9})</td>
</tr>
<tr>
<td>CSWA 26</td>
<td>19</td>
<td>0.043</td>
<td>824</td>
<td>10.2(^{+0.9}_{-0.7})</td>
<td>4.8(^{+1.2}_{-0.8})</td>
</tr>
<tr>
<td>CSWA 28</td>
<td>17</td>
<td>0.068</td>
<td>1164</td>
<td>17.8(^{+0.8}_{-0.8})</td>
<td>7.1(^{+1.8}_{-1.3})</td>
</tr>
<tr>
<td>CSWA 30</td>
<td>6</td>
<td>0.028</td>
<td>165</td>
<td>3.7(^{+0.2}_{-0.3})</td>
<td>3.8(^{+1.2}_{-1.2})</td>
</tr>
<tr>
<td>CSWA 36</td>
<td>8</td>
<td>0.067</td>
<td>534</td>
<td>6.9(^{+0.4}_{-0.4})</td>
<td>4.7(^{+1.4}_{-0.8})</td>
</tr>
</tbody>
</table>

Table 3.2: Errors to luminosities are reported at 1\(\sigma\). Temperature errors are reported at the 90% confidence
level. We note that all exposure times (with the exception of CSWA 26) were expected to yield 100 net
counts based on the group scaling relations of Lopes et al. (2009). All targets, except for CSWA 26, were
1.5-11.6 times brighter than expected indicating that these systems have more hot gas or have higher gas
temperatures than scaling relations predict.

### 3.3.3 HST Observations and Processing

Joint HST ACS observations of CSWA 11, 14, 26, and 30 were taken to supplement
existing archival HST and Gemini images of other CASSOWARY catalog members and to
help resolve exactly what galaxies go into assembling a fossil BGG. To match archival data
methods and exposure times, three line-dithered exposures were drizzled together using the
standard pipeline to form composite images in the F475W, F606W, and F814W bands with
total exposure times for each filter coming to around 4100 seconds. These three bands allow
us to create high resolution color composite images of these strong lensing systems and identify complex merging environments that were previously unresolved in SDSS. To help disentangle overlapping stellar envelopes near the BGGs, we fit each galaxy to both Sersic and exponential profiles using galfit which simultaneously finds solutions to multi-component fits for multiple galaxies; our goal is to determine which galaxies are being cannibalized in forming a fossil BGG and thus generate more accurate progenitor luminosity functions for comparisons with previous work by Johnson et al. (2018).

3.4 CHANDRA RESULTS

3.4.1 X-ray Scaling Relations

Lopes et al. (2009), using 183 systems, found group scaling relations for radius \( R_{200} \), mass \( M_{200} \), X-ray luminosity \( L_X \), and hot gas temperature \( T_X \) all as functions of the number of 0.4\( L^* \) red ridge elliptical member galaxies \( N_{200} \). Earlier studies found similar relations, however these utilized mostly rich clusters (Rykoff et al. 2008; Markevitch 1998). These scaling relations show the expected trend of more X-ray luminous systems housing more bright galaxies along with having higher global hot gas temperatures and are a good way to see if any given subset of galaxy systems deviates from the norm. For additional comparisons, we include galaxy groups from Zou et al. (2016)
who took care to account for any biases in their sample, and we see their systems are consistent with previous group scaling relations formed using more massive clusters, demonstrating the fidelity of our chosen scaling relations. Our Chandra snapshots reveal that both nearby, non-lensing fossils (data from Miller et al. 2012; Bharadwaj et al. 2016), as well as the CAS-SOWARY fossil progenitors generally lie above the \( L_X - T_X \) relation with our progenitors showing a total temperature elevation of \( 2.3\sigma \) significance (Figure 3.1; Table 3.2). Bharadwaj et al. (2016) found a similar offset using only fossil systems, where their fossils trended above established \( L_X - T_X \) relations by a total of \( 2.3\sigma \). A search through the Chandra archive for any data on our non-lensing fossil progenitors identified from our previous study (Johnson et al. 2018) yielded one result which has been included in Figure 3.1. Surprisingly, this non-lensing fossil progenitor is consistent with our lensing progenitors.

We also observe a trend among our lensing fossil progenitors of being over-luminous in X-rays compared to their group richness by a total of \( 8.8\sigma \) significance (Figure 3.2). This is not seen in the nearby fossils from Miller et al. (2012) which could mean this effect is either limited to the progenitor phase, redshift dependent, or is a bias in our sample, as all our progenitors are strong lenses. One explanation for this behavior is rooted in the definition of a fossil progenitor, namely that they are systems with imminent/ongoing merging. This merging has the potential to trigger active galactic nuclei (AGN) thereby heating up the surrounding material. Additionally, we could be seeing the effects of group mergers (e.g. CSWA 2) which would introduce shocks increasing both the temperature.

![Figure 3.2: The \( L_X - N_{200} \) relation showing how strong lensing fossil progenitors are over-luminous by a total of 8.8\( \sigma \) in X-rays for their bright galaxy count. For comparison nearby, non-lensing fossil systems from Miller et al. (2012) are also included. Error bars are reported at 1\( \sigma \).](image-url)
ture and X-ray luminosity of the ICM. As for the Miller et al. (2012) fossils, it was observed that their hot gas halos were oftentimes disturbed and asymmetric which is not expected for relaxed systems. Therefore, it could be that some observed fossils are young enough to still show the elevated temperatures and luminosities seen in their progenitors. This possibility is supported by the lack of cool-cores in many nearby fossils (Sun et al. 2004, Khosroshahi et al. 2004, 2006) indicating that gas cooling time scales can exceed galaxy merger time scales which would produce a non-cool core fossil system for a time.

We see a similar deviation in the $T_X - N_{200}$ relation with our lensing progenitors exceeding typical scaling relations by a total significance of $2.3\sigma$ (Figure 3.3). However, in this case the Miller et al. (2012) fossils seem to follow along with the lensing progenitors in having elevated global hot gas temperatures. While shocks due to group interactions could cause a system to have elevated temperatures, the likelihood that this is responsible for all fossil system deviations is slim since this effect would be transient. A lensing bias may be at play here, but if that were true the non-lensing fossils should not follow the same trend as the lensing progenitors. Instead, it could be that fossil systems and their progenitors possess deeper potential wells than other similar richness non-fossils. This would serve to both hold on to more group gas and have that gas be at a higher temperature than otherwise predicted (based solely on counting galaxies), however we cannot completely rule out the possibility that our sample is biased.

It is important to note that some deviations in scaling relations using $N_{200}$ can be expected

![Figure 3.3: The $T_X - N_{200}$ relation also showing a total progenitor temperature elevation of $2.3\sigma$ significance relative to typical scaling relations. It is interesting that even non-lensing fossils appear to follow our lensing progenitors suggesting that the lensing bias may not appear in this particular relation.](image)
for any given fossil system. By definition, fossil BGGs are formed via cannibalization of bright
member galaxies; this decreases the galaxy count while maintaining the total group gas and
stellar mass. Such deviations would shift fossils left on relations serving to make them appear
slightly over-luminous/hotter than predictions. However, this effect alone is insufficient to
explain the magnitude of our progenitor offsets, as even the most massive and crowded fossil
progenitor in our sample (CSWA 26) will only cannibalize ten $0.4L^*$ galaxies by $z = 0$,
representing only a 12% decrease in $N_{200}$ due to merging. The other seven progenitors only
have between two and five bright galaxies to be cannibalized before fossil status is achieved.
We also find no correlation between time until fossil status is achieved and $L_X$ or $T_X$, however
a larger sample size may change this in the future.

3.5 HST RESULTS

3.5.1 Improved Progenitor Luminosity Function

Figure 3.4: HST images of the inner regions of seven fossil progenitors (CSWA 10 was observed by Gemini
in the $r$-band) with X-ray contours overlaid in green. Contours begin at 2$\sigma$ confidence above the background
emission and increase by 1$\sigma$. White bars denoting 100 kpc at each system's redshift are in the upper right
corner of each image. Asymmetric emission is seen in CSWA 11, 26, and 36 with elevated core temperature
observed in CSWA 26 and 28. An offset between CSWA 36's BGG and the X-ray centroid of 60 kpc can
also be seen.
Figure 3.5: *Left:* Galaxy luminosity functions of all CASSOWARY catalog members using SDSS photometry refined by all available *HST* imaging to resolve BGGs in mid-assembly. The lines indicate the best fit Schechter functions to the data. The data diverge near $10^{11} L_\odot$ clearly demonstrating that progenitors are the transitional phase between non-fossils and fossils. *Right:* The same data with the exception that all BGGs have been removed. Here, we see each type of system being consistent with the others; this means that optically the BGG contains most of the differences between fossils and non-fossils on average at this epoch of a fossil’s life. Error bars are reported at 1σ.

Previous observations of our CASSOWARY progenitors was limited to SDSS images; and, as our sample’s average redshift is $z \sim 0.4$, we were unable to resolve exactly what galaxies were in close proximity to the assembling fossil BGG. This meant our galaxy luminosity functions in Johnson et al. (2018) were incomplete at the bright end for the progenitor sample. Using recently obtained *HST* imaging, we now have resolved images of the inner regions of all eight progenitors allowing us to refine the bright end of the progenitor luminosity function. A Schechter function (Schechter 1976) of the form

$$\Phi = \phi^* (L_{gal}/L^*)^\alpha e^{-(L_{gal}/L^*)}$$  \hspace{1cm} (3.1)$$

was used to find the luminosity function where $\phi^*$ is a normalization, $L^*$ is the characteristic galaxy luminosity power-law cutoff, and $\alpha$ is the faint end slope. We used the *galfit* program to simultaneously fit all interacting/nearby galaxies in the unresolved area for SDSS to Sersić and exponential disk functions in the F606W and F814W bands with the goal
being to find the $r$-band luminosity of all galaxies that will be cannibalized by the BGG. We find that two previously classified fossil systems (CSWA 4 & 11) using SDSS resolution are in actuality still assembling their BGGs (see Figure 3.4). Upon reclassifying these as progenitors and deconvolving all galaxies in the previously unresolved inner regions of our eight fossils, we find the galaxy luminosity function separation between fossil, progenitors, and non-fossils is preserved and even refined compared to our findings in Johnson et al. (2018) (Figure 3.5). Previously, the progenitor luminosity function trended closer to the fossil function at intermediate luminosities. We believed this was due to us missing intermediate mass galaxies in close proximity to the BGG due to SDSS’s angular resolution limit. By now resolving many new galaxies at the progenitors’ centers, the progenitor function now firmly sits between fossils and non-fossils for $L_{gal} > 10^{11} L_\odot$. Upon removing all BGGs from the luminosity functions, we see all three becoming consistent with one another. We believe this is a resolution issue, as by combining fossil and progenitors into one data set, the expected differences from non-fossils is seen\(^2\). We note that the reclassifying of two previously identified fossil systems as progenitors increased the uncertainties in the fossil luminosity function by a considerable amount, making it harder to distinguish small variances between data sets. Additionally, we truncate our data at the absolute $r$-band magnitude $M_r < -19.5$ which corresponds to the completion threshold of SDSS at our most distant CASSOWARY group.

In our previous work (Johnson et al. 2018), we were unable to resolve any significant $L^*$ deficit in our fossil system luminosity function due to there being a relatively low number of fossils compared to non-fossils. However, by combining $z \sim 0.4$ fossils and progenitors into one ‘fossil-like’ category, a slight but significant deficit is observed between $10^{10} < L_{gal} < 10^{11} L_\odot$ (Figure 3.6). While less significant than what is expected in nearby ($z < 0.2$) fossil systems due to the rapid widening of the BGG magnitude gap at this epoch (Gozaliasl et al. 2014), this small deficit should grow as $z$ decreases and more galaxies are cannibalized by the BGG thus widening both the bright end and faint end deviations from non-fossils as

\(^2\)The best fits for each category are found by excluding BGGs, as these are the result of galaxy reprocessing over time and are consequently not well represented by a Schechter function.
fainter galaxies disappear from the population and the bright BGG increases in luminosity.

We also notice the best fit parameter $L^*$ is slightly lower for the ‘fossil-like’ fit compared to the non-fossil fit, however it is not statistically significant. It could be that this separation in $L^*$ increases with deceasing redshift as more galaxies are cannibalized by the BGG, as Zarattini et al. (2015) found that fossils at $z < 0.25$ have characteristically lower $L^*$ values than non-fossils. They go on to find differences for the faint end slopes of the Schechter functions, however the higher average redshift of our groups limits our ability to fully account for faint member galaxies.

Since we know which galaxies have the potential to be incorporated into the still forming fossil BGG, we can fast forward each system to a $z = 0$ frame (where all our progenitors would be considered fossils) and then compare the new fossils against our projected $z = 0$ non-fossils. By adopting the conservative merger time scale used in Kitzbichler & White (2008), who utilized the projected separation and total mass of galaxies to estimate the time until two galaxies merge, we identify all member galaxies that could merge with the BGG within the system’s look back time and add their luminosities to the BGG to create a probable $z = 0$ BGG. After this, we find that the $L^*$ discrepancy between fossils and non-fossils grows slightly ($L^*_{fossil} = 3.3 \times 10^{10} \, L_\odot$ and $L^*_{non} = 2.9 \times 10^{10} \, L_\odot$) and is significant, indicating that fossil and non-fossil BGGs must grow at roughly similar rates. This appears to contradict findings in the Millennium simulation by Gozaliasl et al. (2014) who found that fossil BGGs rapidly grow their magnitude gap beginning around $z \sim 0.2$ implying a simultaneous rapid depletion of
other member galaxies. If this is true, in order for the fossil/non-fossil luminosity function difference to exist, the fossil BGGs must have formed earlier than their non-fossil counterparts. This supports other findings by Gozaliasl et al. 2014 who saw that on average, fossil BGGs assembled most of their mass before $z = 0.5$. One possible cause for the slower than expected growth of fossil BGGs (or faster than expected growth of non-fossil BGGs) lies with our sample all being strong gravitational lenses. Since each of these systems are acting as strong lenses, they already must be concentrated systems thereby making each CAS-SOWARY group inherently more fossil-like than a typical non-lensing system. This higher than average mass concentration has the potential to cause lensing systems to evolve differently than comparable non-lensing systems, and thus make direct comparisons to N-body models more difficult.

We also begin to visually see the known $L^*$ galaxy ($10^{10} < L_{gal} < 10^{11} L_\odot$) deficit in member galaxies in our projected $z = 0$ fossils when compared to our projected $z = 0$ non-fossils (Figure 3.7). One can take the total light in this observed $10^{10} < L_{gal} < 10^{11} L_\odot$ deficit of fossil systems and compare that to the total excess of light seen for $L_{gal} > 10^{11} L_\odot$. Since both populations (fossils + progenitors and non-fossils) have a comparable total stellar content (within a factor 1.6) we can see if the ‘missing’ light at the faint end matches the ‘excess’ seen at the bright end of the luminosity function for fossils. We find that for both the rest frame (unmerged) and $z = 0$ (merged) functions, these two deficits/excesses are within

![Figure 3.7: The projected $z = 0$ galaxy luminosity functions of all eventual fossil systems (fossils + progenitors) found by numerically merging all member galaxies that could merge within each system’s look back time to create a probable final fossil BGG. The same was done for non-fossils for consistency in comparisons, although very little change was seen in its projected luminosity function. The projected fossil deviation for $L_{gal} > 10^{11} L_\odot$ galaxies is slightly more than what is observed at $z \sim 0.4$, and a deficit in $10^{10} < L_{gal} < 10^{11} L_\odot$ still present.](image-url)
7% of each other supporting the idea that fossil BGGs are not simply an over-luminous central galaxy. Rather, they are more likely a product of the redistribution of the total group stellar content that has been focused into one galaxy, as this should preserve any differences in luminosity functions provided fossil and non-fossil BGGs grow in the same manner and at similar rates.

Fast forwarding each CASSOWARY system to \( z = 0 \) yielded an unexpected finding where our projected \( z = 0 \) non-fossil luminosity function matched our rest frame (\( z \sim 0.4 \)) ‘fossil-like’ function to a surprising degree where a K-S test shows each coming from identical distributions. This suggests that CASSOWARY fossils and progenitors are simply \( \sim 4 \) Gyr more evolved than non-fossils making age a defining factor in fossil systems. These findings support the hypothesis that fossil systems are a phase of galaxy system evolution that all groups will eventually pass into or even through as new galaxies simultaneously fall into the group and existing galaxies are cannibalized by the BGG (von Benda-Beckmann et al. 2008; Cui et al. 2011). However, this does not explain the higher than expected X-ray luminosities and temperatures seen in progenitors, indicating that they are not relaxed systems. It is possible that this result is due to the strong lensing bias telling us that our lensing progenitors have a deeper potential well than non-lensing non-fossils of comparable richness.

3.6 INDIVIDUAL SYSTEMS OF NOTE

3.6.1 CSWA 26

Our \textit{Chandra} snapshots were designed to give the first definitive X-ray detections of eight fossil progenitors, however two systems were luminous enough for us to find additional information. This included rough radial temperature profiles which is a key component in identifying which formation track a specific fossil progenitor is following. We see a clear asymmetry in CSWA 26’s hot gas with a 50 kpc offset between the lensing center of mass and the X-ray centroid (Figure 3.4). We also observe a temperature increase at the group center going from \( 2.0^{+0.7}_{-0.4} \) keV in a 280-420 kpc annulus centered on the BGG, up to \( 6.8^{+1.7}_{-1.3} \)
keV for the innermost circle of 280 kpc. This factor of three increase in gas temperature is not consistent with a relaxed system but instead mirrors the previously studied fossil progenitor CSWA 2 where it is believed a group merger was shock heating the gas at the center of the group (Irwin et al. 2015) making CSWA 26 a candidate for another group merger fossil progenitor but a factor of two to three times more massive. This is supported optically by SDSS spectroscopic redshifts for the first \((z = 0.336)\) and third \((z = 0.341)\) rank member galaxies showing a 1030 km s\(^{-1}\) radial velocity difference. For comparison, the radial velocity difference between the two ‘eyes’ of the CSWA 2 is 1100 km s\(^{-1}\). While SDSS photometric redshift (photoZ) data for all CSWA 26 member galaxies suggests a bimodality centered about the first and third rank galaxies, spectra are needed to confirm this as a second group merger fossil progenitor.

### 3.6.2 CSWA 28

Most unexpected of all was the \(z = 0.418\) progenitor CSWA 28 which exceeded X-ray luminosity predictions by an order of magnitude. This optically unassuming \(N_{200} = 31\) fossil progenitor, by almost all accounts, seemed to be a relaxed system with little major merging left to complete before the fossil BGG was fully assembled. Archival \(HST\) imaging showed smooth isophote contours in and around the BGG with the only oddity being a 62 kpc offset between the lensing center of mass and the BGG. What was expected to be \(\sim 100\) net counts detection was instead over 1100 making CSWA 28 the most luminous fossil progenitor out of our sample. CSWA 28 also shows the highest gas temperature of our sample at \(7.1^{+1.8}_{-1.3}\) keV, which is expected from a massive cluster, not a poor fossil progenitor. Like CSWA 26, we observe a radial temperature spike in the central regions of CSWA 28 from \(3.0^{+0.7}_{-0.2}\) keV at 280 kpc to \(9.2^{+5.3}_{-2.2}\) keV within 170 kpc meaning this could also be another group merger but in a post merger stage, as optical isophotes are smooth and no bright galaxies are nearby. Interestingly, the BGG aligns well with the X-ray centroid; this means the lensing center of mass is being affected by something outside the system. As with CSWA 26, there are

\(^{3}\text{All temperature errors are reported at the 90% confidence level}\)
currently no spectra of CSWA 28 making further investigation difficult.

### 3.6.3 CSWA 36

While CSWA 36 did not yield enough counts to identify the existence of any non-cool cores, the global temperature is higher than the $T_X - N_{200}$ relation by 4.8σ, and we are able to see a significant elongation of the hot gas to the southwest of the BGG (Figure 3.4). There is also a 60 kpc offset of the BGG to the X-ray centroid which could be, again, due to a group merger scenario where the BGG has been temporarily pulled away from the center of the dark matter potential; however to verify this, spectra are needed to search for the velocity distribution of all group members. If CSWA 36 is confirmed to be another group merger fossil progenitor, that would mean ~ 45% of the X-ray detected CASSOWARY progenitors (CSWA 2, 26, 28, and 30) show evidence of following the group merger fossil formation track suggesting this mechanism could contribute significantly to the total observed fossil fraction.

### 3.7 SUMMARY

#### 3.7.1 X-ray Conclusions

In this work, we find from Chandra ACIS-S snapshots of eight previously unobserved CASSOWARY fossil system progenitors systematic $L_X - T_X$, $L_X - N_{200}$, and $T_X - N_{200}$ relation offsets for progenitors making them brighter and hotter than what is expected for non-fossils of similar galaxy richness. Progenitors are found to be between 2σ and 9σ removed from existing X-ray scaling relations, showing these deviations are statistically significant. These offsets could be due to progenitors having deeper dark matter potential wells than non-fossils (leading to more retained hot gas at higher temperatures), progenitors undergoing group mergers which would shock heat gas and also introduce more X-ray gas into the system, or a bias caused by our targets being strong gravitational lenses. We rule out the possibility that these temperature deviations are a result of $L^*$ galaxies being cannibalized by the BGG thus lowering $N_{200}$ and sliding our progenitors away from expectations by noting that
an average of only two to three $L^*$ members will merge with the BGG by $z = 0$. While noticeable, cannibalization alone does not explain the 3$\sigma$ total offset observed.

We observe that our progenitors are more consistent with fossil systems than non-fossils for relations involving hot gas temperature $T_X$ supporting the hypothesis that fossil-like systems are centrally concentrated before the fossil BGG has finished its assembly. However, nearby fossils are not elevated on the $L_X - N_{200}$ relation while our progenitors are. This suggests that the elevated $L_X$ we see for progenitors might be transitory and a result of their presently tumultuous environment possibly shock heating some of the gas. It is also possible that AGN could inject a substantial amount of energy into the ICM thus temporarily increasing the group’s X-ray luminosity. However, we find it curious that out of nine X-ray detected fossil progenitors, only one (CSWA 2) shows evidence of an active AGN of $L_X > 10^{41}$ erg s$^{-1}$ in a member galaxy even though all possess congested central regions where major merging is either imminent or ongoing.

Asymmetries in X-ray emission for CSWA 26 and 36 and elevated core temperatures for CSWA 26 and 28 support the validity of a group merger mechanism for fossil formation and demonstrate that it may play a significant role in the total fossil fraction seen at low redshift today. Finding tentative evidence for temperature spikes in CSWA 26 and 28 also aids in explaining the existence and unexpectedly high number of nearby fossil systems that do not possess cool cores, as X-ray cooling time scales are typically longer than galaxy merger time scales. This means that these two progenitors should be classified as fossil systems before the hot gas at their cores has had a chance to cool significantly akin to the fossil progenitor CSWA 2.

3.7.2 HST Conclusions

Using new HST observations of our eight strong lensing fossil progenitors, we are able to resolve the complex merging environments expected to exist in progenitors. Two fossil systems identified via SDSS imaging (CSWA 4 and 11) were found to have unresolved $L^*$ galaxies within two magnitudes of their BGGs in mid cannibalization thereby shifting them
from fossils to progenitors. Resolving more intermediate mass galaxies near progenitor BGGs such as these allows us to refine the galaxy luminosity functions for our fossil progenitors, the results of which support our previous findings that progenitors are the transition phase between non-fossils and fossils. Interestingly, removing all BGGs from the data cause our fossils, progenitors, and non-fossils to become consistent with one another, however the expected differences from non-fossils appeared when the fossil and progenitor samples were combined. We wish to note that the reclassifying of two fossils to progenitors caused fossil luminosity function uncertainties to grow substantially possibly washing out subtle differences such as these. We also note that our data were limited to $M_r < -19.5$, as this is the SDSS completeness threshold for our most distant system. As much debate surrounds the faint end behavior of the fossil luminosity function ($M_r > -18.0$), it is possible that differences between our fossils and non-fossils exists outside the BGGs but in a place we are unable to probe with this data set.

By combining galaxies from the fossil and progenitor categories to form a ‘fossil-like’ class of groups, we find the expected deficit $10^{10} < L_{gal} < 10^{11} L_\odot$ members whose combined luminosity matches within 7% the excess luminosity seen in fossils for $L_{gal} > 10^{11} L_\odot$. This is preserved even after fast forwarding each system to a $z = 0$ reference frame by numerically merging eligible member galaxies according to the system’s look back time and the merger time scale from Kitzbichler & White (2008). We also notice that the ‘fossil-like’ and non-fossil luminosity functions evolve together when placed in a $z = 0$ frame, implying that their BGGs are growing at comparable rates which appears to contradict findings in the Millennium simulation by Gozaliasl et al. (2014). At the same time, comparable BGG growth rates for our fossils and non-fossils requires our fossil BGGs to be assembled earlier than the non-fossils’, otherwise the known fossil luminosity function deviation at the bright end would never form. This early fossil BGG assembly time supports other findings from Gozaliasl et al. (2014) who saw most of the fossil BGG mass assembly occur before $z = 0.5$.

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CHAPTER 4

MOTIVATION FOR FUTURE RESEARCH

4.1 A RICH PROBLEM

An intriguing yet incomplete picture of fossil galaxy systems is being uncovered in astronomy through the use of simulations and observations, some of which appear to yield consistent results and some contradictory. Are fossil systems the extended tail of galaxy cluster and group populations? Are they the end product of group evolution billions of years in the future? Are they natural phases in the normal evolution of systems? Are they a unique class of object all their own with different initial conditions than typical galaxy groups? All these questions, while actively being addressed by us and others, are yet incomplete in their explanations, implying this is a rich field of study with further questions available to discover.

Fossil systems were classically thought to be the remnants of highly evolved systems and represented a cosmological wealth of information, as scientists could in theory probe these structures to find properties of the early universe (Jones et al. 2003). However, findings in N-body simulations showed that while some could be old, undisturbed systems, fossils can be formed as late as $z \sim 0.3$ complicating the previous model (Kanagusuku et al. 2016). Further, the discovery of $z < 0.2$ fossil systems that did not possess cool X-ray cores showed that these systems had recent, group scale, energetic events of some kind contradictory to the claim that all fossils are undisturbed. These results told us that finding young fossil systems, or fossil systems in mid BGG assembly, should be feasible if one looks in the correct epoch
of cosmic time. The discovery of the Cheshire Cat fossil progenitor by Irwin et al. (2015) showed that this was indeed the case and further, the fossil making process can be quite violent. Some fossils could fall under the classical definition of a highly evolved, undisturbed group where most intermediate mass galaxies have been cannibalized by the BGG. Others could form via the group merger of two or more separate systems. Finally, some systems could have initially formed with a massive central elliptical that was efficient at turning gas to stars and effectively starved other galaxies of material. Such a system would effectively be born a fossil system.

Many studies have involved individual, or a small number of, fossils attempting to measure their odd or interesting properties. This has over time created a substantial archive of fossil systems which allows us to study their average properties across a range of group masses and redshifts in more meaningful ways. Our work has helped bolster this collection and added a new category: fossil progenitors. We can now directly observe systems in the process of becoming fossils allowing us to begin comparing observations to simulations.

4.2 QUESTIONS TO ADDRESS

Now that fossil progenitors have been found, a natural question to ask is how often certain formation tracks are followed. In other words, how many of today’s fossils formed via secular evolution, and how many formed via group mergers? In principle, this question is a simple one to address: do the velocity dispersions and redshift distributions of member galaxies suggest a recent group merger? If one obtained spectra of all nearby galaxies in a progenitor, one could check for bimodalities centered around bright galaxies and determine, based on radial velocity difference of each peak, if these two systems are interacting. The lack of a bimodality would be suggestive of the progenitor evolving internally, cannibalizing its own member galaxies. After some time surveying multiple systems, one could arrive at predictions of fossil formation track rates to check against the simulated rates.

Locating group merger progenitors can also be done in X-rays if one looks for instances of
elevated gas temperatures consistent with the shock heating of the ICM as two halos interact. Specifically, the finding of a non-cool core fossil progenitor would be highly suggestive of either a group merger scenario (akin to the Cheshire Cat) or a recent AGN injecting energy into the group core. Significant asymmetries in the hot gas halo and BGGs offset from the X-ray centroid would also be indications of recent, group scale interactions. This method can also be extended to fossil systems with already formed BGGs. Non-cool core fossils, like those found by Miller et al. (2012), are likely to be younger than fossils with cool X-ray cores. These must have also undergone a recent, tumultuous event, as X-ray cooling time scales for galaxy groups are typically on the order of a few Gyr. These findings would augment optical results and form a more complete picture of fossil formation track rates and even aid in answering if fossils are a unique class of system. If many fossils are found to have taken the group merger formation track, this would support the notion that fossils are not a unique class of object; they are likely a branch of system evolution. Conversely, if systems like the Cheshire Cat are rare, there may indeed be something inherently odd about the group properties of fossil systems that separates them from non-fossils.

There is also an outstanding question regarding the role of strong gravitational lensing and how it biases our sample in the X-ray regime. We determined optically that a strong lensing group is $\sim 5$ times more likely to be identified as a classical fossil system. This is unsurprising, as centrally concentrated systems would inherently make good strong lenses. Additionally, we found that strong lensing progenitors had statistically different galaxy populations than non-lensing progenitors, further highlighting the presence of a strong lensing induced bias. With the inclusion of our X-ray results showing our lensing progenitors lying $2.1\sigma$ above typical group $L_X - T_X$ scaling relations, this raises questions regarding how far the bias extends into the hot gas component of lensing systems, if at all. Currently, there is a lack of archival non-lensing progenitor and lensing fossil system X-ray data making it difficult to fully identify and account for any bias.
4.3 PROPOSED FUTURE OBSERVATIONS AND PLANS

This, in part, led us to propose joint Chandra ACIS-S and multi-wavelength HST observations of eight strong lensing fossil/non-fossil systems and eight non-lensing fossil progenitors for Cycle 20 totaling to 434 ksec of Chandra observing time. This data will either confirm the presence of an X-ray strong lensing bias and allow us to correctly interpret our initial X-ray findings or show that the bias is restricted to optical light. If the elevated X-ray temperatures and luminosities in progenitors are not due to a bias, this would increase the likelihood that progenitors are a distinct phase of group evolution that has far reaching consequences on the entire group dynamic.

The previously obtained Chandra snapshots of eight lensing fossil progenitors discussed in Chapter 3, while revealing, were not long enough to form radial temperature profiles or gas mass profiles for all eight targets. Temperature profiles are needed to identify any X-ray cool cores (which correlate to fossil formation mechanisms), and gas/gravitational mass profiles open a new avenue of study allowing us to fit each group to a Navarro-Frenk-White (NFW) dark matter profile (Navarro et al. 1996). The value of the free parameter ‘c’ in this profile represents the concentration of the mass distribution and is a point of contention in the literature for fossil systems (Sun et al. 2004, 2009; Khosroshahi et al. 2004, 2006). We are also currently working on modeling the strong gravitational arcs seen in the CASSOWARY HST images which will provide additional independent mass anchors at the arcs’ radii improving the NFW fit. Finding the value of this parameter for a still-forming fossil would be invaluable in determining if fossils have systematically higher concentrations than non-fossils. Preliminary results for the primary arc near CSWA 26 give a lensing mass off \( M_{\text{lens}} = 4.0 \times 10^{13} \, M_\odot \) for the inner 64 kpc of the group which implies a high c-value. For comparison, this is roughly equal to 16 times the mass of the Local Group confined within \( \sim 2.5 \) Milky Way diameters. To this end, we plan to propose future XMM-Newton observations of fossil progenitors, as XMM-Newton offers a larger collecting area than Chandra allowing us to reach higher photon counts with shorter exposure times.
We also plan to continue research in optical light by utilizing the up-and-coming Javalambre Physics of the Accelerating Universe Astrophysical Survey (J-PAS) which is using 56 narrow band filters to achieve near spectroscopic quality redshifts with photometry\(^1\). This setup is ideal for quickly and efficiently mapping the redshifts of progenitor member galaxies to definitively identify membership statuses and instances of group mergers, furthering our goal to better constrain fossil formation mechanism rates.

\(^1\)http://www.j-pas.org
CHAPTER 5

OVERALL CONCLUSION

Fossil progenitors, which were predicted to exist in simulations (Kanagusuku et al. 2016), have been found in the field. We have identified a number of new strong lensing fossil systems and fossil progenitors in the CASSOWARY catalog and determined that these progenitors fall between fossils and non-fossils on galaxy luminosity functions (Johnson et al. 2018). This challenges the classical definition of all fossils being old and undisturbed systems; instead it is more likely that fossils can be formed a few different ways. Secular group evolution where intermediate mass galaxies slowly lose angular momentum via dynamical friction, sink to the center of the group, and are cannibalized by the BGG can account for the observed fossil population with cool X-ray cores. More violent group mergers can also give rise to fossil systems once the separate BGGs merge into one dominant galaxy; these can account for the observed non-cool core fossil population. A small subset of cool core fossils could be ‘born that way’ if the BGG was unusually efficient at turning gas to stars at the group’s inception, however we expect this to only be a viable mechanism for the poorest of fossil systems ($N_{200} \sim 5$). We identify an optical bias where strong lensing systems are a factor of $\sim 5$ more likely to be a classical fossil system. Comparing lensing and non-lensing progenitors showed that lensing progenitors had different galaxy populations than non-lensing progenitors reinforcing the existence of a bias.

We follow up on these findings by observing eight CASSOWARY progenitors at varying stages of time until fossil status is achieved. We find no correlation between a progenitor’s X-ray properties and its evolutionary stage, however we do see a systematically high X-ray
luminosity and temperature for all our progenitors. This $2.3\sigma$ elevation in the $L_X - T_X$ relation compared to non-fossils is consistent with previous findings from Bharadwaj et al. (2016) who found that non-lensing fossils were also elevated by $2.3\sigma$. The strong lensing bias may extend into the X-ray regime, however our progenitors following the non-lensing fossil trend means the bias could be weak or nonexistent at these wavelengths. *HST* imaging of these eight progenitors revealed previously unresolved complex merging environments at the centers of our progenitors. We were able to disentangle individual galaxies using modeling routines and refine existing progenitor galaxy luminosity functions. The improved fits verify that progenitors are indeed the transition phase between non-fossils and fossils. Numerically fast forwarding each CASSOWARY system to a $z = 0$ reference frame by ‘merging’ all eligible member galaxies near the BGGs showed that the differences seen between fossils and non-fossils are maintained over time. Interestingly, the fast forwarded non-fossils are indistinguishable from the rest frame ($z \sim 0.4$) fossil systems indicating that fossil systems may be a more evolved version (by $\sim 5$ Gyr) of the non-fossils. This supports the notion that fossil systems may form before non-fossils; this would give them a head start in assembling a massive BGG and supports findings by Gozaliasl et al. (2014).

We are currently attempting to model the multiple strong lensing events seen in the *HST* snapshots to begin finding accurate lensing masses and have preliminary results for the fossil progenitor CSWA 26 that seem to show it having a high concentration parameter. Since multiple arcs at varying radii are visible in the images, we can use each enclosed mass as an anchor in an NFW profile fit, the goal being to constrain the concentration parameter ‘$c$’ as much as possible. This is in preparation for future *XMM-Newton* observing proposals which will allow us to find radial temperature profiles to identify cool X-ray cores and gas/gravitational mass profiles for fossil progenitors. We also proposed additional *Chandra* and *HST* snapshots of eight CASSOWARY fossil/non-fossil systems and eight non-lensing progenitors for Cycle 20 to fill gaps in our understanding of the strong lensing bias and provide an accurate baseline for comparisons. Additionally, we plan on taking advantage
of J-PAS and its unparalleled ability to quickly and accurately find photometric redshifts of near spectroscopic quality using 56 narrow band optical filters. By observing our fossil progenitors using J-PAS, we will be able to definitively find group members and all instances of ongoing group mergers which will aid in finding which fossil formation track is dominant.

In conclusion, we now have a better grasp on how fossil systems form, as predictions in numerical simulations have been verified via observations. Many expect fossil systems to have concentrated centers, and this has been indirectly verified by noticing that strong lensing systems are $\sim 5$ times more likely to be fossil systems than comparable non-lensing systems. The explanation for the existence of the supposedly contradictory non-cool X-ray core fossil system has also been strengthened by observing additional progenitors with evidence of non-cool cores akin to the Cheshire Cat fossil progenitor. Such systems appear to be group mergers which will finish assembling their fossil BGGs before the shocked gas would have time to cool, thus leading to a non-cool core fossil (at least until the gas sufficiently cools).

While the picture is still unclear on whether or not fossils are a unique type of galaxy system or a phase of typical group evolution, our proposed observations with Chandra and XMM-Newton will aid in determining this by clearly showing us their group properties beyond what defines them as fossil systems.
REFERENCES


