Chandra and HST Snapshots of Fossil System Progenitors

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Abstract

The search for the progenitors to today’s fossil galaxy systems has been restricted to N-body simulations until recently, when 12 fossil progenitors were identified in the CASSOWARY catalog of strong-lensing systems. All 12 systems lie in the predicted redshift range for finding fossils that are in the process of assembling their brightest group galaxy (BGG), and all show complex merging-like environments at their centers. Here, we present Chandra and Hubble Space Telescope snapshots of eight of these strong-lensing fossil progenitors at varying stages of evolution. We find that our lensing progenitors exhibit higher than expected 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.

Key words: galaxies: clusters: intracluster medium – galaxies: groups: general – gravitational lensing: strong

1. 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 systems are generally thought to have formed oversized brightest group galaxies (BGGs) over time as dynamical friction slowly drags bright member galaxies down to the BGG, thus growing the BGG via cannibalization. Given enough merging, a 2.0 mag gap in the r-band between the BGG and the next brightest member within half the virial radius of the system will be formed; this results in a fossil system (Jones et al. 2003). These fossil systems were distinguished from lone, large ellipticals by requiring them to possess a hot gas halo of \( L_{X, bol} \geq 10^{42} h_{50}^{-1} \text{erg s}^{-1} \). This process 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 challenged by the existence of many nearby fossil systems \((z \lesssim 0.1)\) that show heated gas in their cores. For a time, core heating via X-ray/radio active galactic nuclei (AGNs) and processes such as turbulent heating were believed to explain the existence of some of these; however, more recent observations of work done by radio emission in fossils and hydrodynamic simulations indicate that cool cores (due to their short X-ray cooling times) cannot be destroyed so easily (Miraghaei et al. 2015; Voit et al. 2017). Thus, the challenge of explaining the existence of non-cool core fossils seems to remain (Khosroshahi et al. 2004, 2006, 2007; Sun et al. 2004). It is therefore likely that some nearby fossil systems may not be as undisturbed and relaxed as previously assumed.

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 assembled and destroyed since \( z < 0.9 \), indicating that 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 that 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 (Trentham 1995). This led to the discovery of the Cheshire Cat strong-lensing fossil progenitor (Irwin et al. 2015).

Identifying the Cheshire Cat as a fossil group progenitor also sheds light on how observed non-cool core fossils might form. Irwin et al. (2015) found that 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 timescales can be longer than galaxy merging timescales, 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 and that they can also be fossil groups themselves; 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 (Belokurov et al. 2009; Stark et al. 2013) of which the Cheshire Cat (CSWA 2) was a member (Johnson et al. 2018).

Seven classical fossil systems and 12 fossil 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. A comparison of each fossil category’s galaxy luminosity functions (fossils, progenitors, and non-fossils) shows the expected differences between fossils and non-fossils and shows that progenitors lie between each function, demonstrating that they are indeed the transition phase between non-fossils and fossils. It was also discovered that there is 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 from 8 of the 12 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 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 event continues, supporting evidence of AGNs of LX > 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 AGNs subtracted out. We chose our fitting regions to be equal to one-quarter of each group’s virial radius (0.25 R_{200}), as the short exposure times made group emission past this point indistinguishable from the background and would only serve to decrease the signal-to-noise ratio. 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 XSPECv12.9 using an APEC thermal model including Galactic absorption (Dickey & Lockman 1990) for each source using tbadv and chisquared 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 to 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.

2. Chandra Analysis

2.1. 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 and observations (Dariush et al. 2007; 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. Out of the 12 fossil progenitors, only 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 ICs. 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.

Of the 12 previously identified fossil progenitors in the CASSOWARY catalog, four were too distant to be detected without increasing our requested time by a factor of five; therefore, we chose to limit this study to the eight brightest/nearest candidates. These eight progenitors vary in their evolutionary stages toward becoming fossils, with the stages corresponding to the expected galaxy merger timescales seen in Kitzbichler & White (2008), ranging from 4 Gyr to only ~100 Myr until the fossil BGG is completed. Chandra snapshot observations were taken of these systems to see how the hot gas component of the groups followed the stellar evolution we observed in SDSS imaging. Additionally, aside from one progenitor that shows tentative optical evidence of being an ongoing group merger, each group has comparable richness and mass, ensuring we are comparing similar systems. Table 1 outlines all our targets along with some basic information about each group that were found in our previous work using galaxy photometric redshift cuts and a combination of color cuts to select red-ridge ellipticals with \( L_{\text{gal}} \geq 0.4L^* \) (N_{200}; Johnson et al. 2018) for use in group scaling relations presented in Lopes et al. (2009) to find \( M_{200} \) and \( R_{200} \). Since \( N_{200} \) is an easily observable quantity in SDSS data (and is widely used as a proxy for key group properties such as mass and radius, which themselves are derived quantities in the absence of deep X-ray imaging), we choose to adopt it as our primary comparison between our sample and comparable systems.

2.2. Chandra Observations and Processing

Chandra ACIS-S snapshots of our eight progenitors were taken during Cycle 17. Since these were previously unobserved, the 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. 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, because 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 AGNs of \( L_X > 10^{41} \text{erg s}^{-1} \) in any of the member galaxies. Background estimates were found by choosing large regions far from group emission with all background AGNs subtracted out. We chose our fitting regions to be equal to one-quarter of each group’s virial radius (0.25 R_{200}), as the short exposure times made group emission past this point indistinguishable from the background and would only serve to decrease the signal-to-noise ratio. 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 XSPECv12.9 using an APEC thermal model including Galactic absorption (Dickey & Lockman 1990) for each source using tbadv and chisquared 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 to 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.

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5 CSWA 26 showed a 2σ 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.
Note. 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 0.4\(L^*\) and mass contained within the virial radius \(R_{200}\) of the group, respectively, according to the Lopes et al. (2009) scaling relations. \(N_{200}\), \(M_{200}\), and the fossil transition timescale are taken from our previous work (Johnson et al. 2018).

### 3. Chandra Results: X-Ray Scaling Relations

Lopes et al. (2009), using X-ray data from the ROSAT All Sky Survey of 127 NoSOCS and 56 CIRS galaxy clusters, 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 the 0.4\(L^*\) red-ridge ellipsoidal member galaxies \(N_{200}\). Earlier studies found similar relations; however, these utilized mostly rich clusters which, along with the observed 40% scatter in mass in the Lopes et al. (2009) relation, explains the slight variations seen between each study (Markevitch 1998; Rykoff et al. 2008). 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 these strong-lensing systems and identify complex merging environments that were previously unresolved in SDSS.

### 2.3. 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 which galaxies go into assembling the eventual 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 s. 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 multicomponent fits for multiple galaxies (Peng et al. 2011); our goal is to determine which galaxies are being cannibalized in forming a fossil BGG and thus to generate more accurate progenitor luminosity functions for comparisons with previous work by Johnson et al. (2018).
Zou et al. (2016), who took care to account for any biases in their sample, and we see that 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 CASSOWARY fossil progenitors, generally lie above the $L_X-T_X$ relation with our progenitors showing a total temperature elevation of 2.3σ significance (Figure 1; Table 2). Bharadwaj et al. (2016) found a similar offset using only bias-corrected fossil systems from the 400d catalog (Voevodkin et al. 2010), where their fossils trended above established $L_X-T_X$ relations by a total of 2.3σ. Our data lie an average of 1.7σ below this fossil-only relation, lending some support to their findings. A possible interpretation is that progenitors could be moving vertically on the $L_X-T_X$ relation, becoming more consistent with existing fossils as the BGG assembles, although more X-ray observations of fossil progenitors are needed to determine how likely this is. A search through the Chandra archive for any data on our previously identified non-lensing fossil progenitors (Johnson et al. 2018) yielded one result, which has been included in Figure 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 overluminous in X-rays compared to their group richness by an average of 8.8σ significance (Figure 2). This is not seen in the nearby fossils from Miller et al. (2012), which could mean that 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 funnel gas into a central black hole and turn on an AGN; however, typical energies injected into the ICM should not disrupt any present X-ray cool core for very long, if at all, based on simulations and observations of an exceptionally massive, nearby fossil’s AGN, RX J1416.4+2315 (Miraghæi et al. 2015; Voit et al. 2017). It is possible that while the existence of a cool core remains through AGN activation, enough energy is deposited into the surrounding medium to detect a slight increase in global temperature. This would remain for a time after the infalling material is exhausted. It could be the case that our sample contains systems that are in the process of their ICM cooling and dimming after mergers and/or AGN firing, meaning these elevated properties of progenitors are like the systems themselves: transitory. This view is supported by observations from Khosroshahi et al. (2017), who found that fossil systems on average have less/weaker AGN activity than non-fossils, most likely due to fossils’ dynamical states. Additionally, we could be seeing the effects of group mergers (e.g., CSAW 2), which would introduce shocks, increasing both the temperature 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 (Khosroshahi et al. 2004, 2006; Sun et al. 2004), indicating that gas cooling timescales can exceed galaxy merger timescales, 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 an average of 2.3σ significance (Figure 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 because 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 by extension their progenitors) inherently possess higher $L_X$ and $T_X$, serving to elevate their
normalizations without affecting that relation’s slope while simultaneously leading to deviations when looking at optical–X-ray relations. One way to achieve this is for fossils to have higher halo masses than non-fossils, which is plausible if they indeed formed earlier than non-fossils (Darush et al. 2007; Khosroshahi et al. 2007). This would serve to both hold on to more group gas over time and have that gas be at a higher temperature than otherwise predicted (based solely on counting galaxies); however, we cannot rule out the possibility that our sample is biased. Additionally, our method of measuring \( N_{200} \) outlined in Johnson et al. (2018) consistently gave results within 10% of other catalogs using SDSS data (when overlap was available). This demonstrates that the dominant source of fossil progenitor offset from the relations cannot be due to errors in \( N_{200} \) and is instead most likely linked to the systems themselves.

It is important to note that some deviations in scaling relations using \( N_{200} \) can be expected 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, making them appear slightly overluminous/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 \( 0.4 L^* \) 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 the time until fossil status is achieved and \( L_X \) or \( T_X \); however, a larger sample size may change this in the future. One could expect to see some cooling in \( T_X \) over time if a \( z \sim 0.4 \) progenitor is left undisturbed. However, given the relatively low gas density of groups (excluding the core), X-ray cooling timescales are too long to notice any appreciable difference in a progenitor’s global temperature given our uncertainties. This has the potential to be more fully addressed by analyzing the cool/non-cool core evolution of progenitors, but this requires deeper X-ray observations.

4. Hubble Results: Improved Progenitor Luminosity Function

Previous observations of our CASSOWARY progenitors were 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 \textit{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

\[
\Phi = \phi^*(L_{gal}/L^*)^\alpha e^{-(L_{gal}/L^*)}
\]

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 \textit{galfit} program to simultaneously fit all interacting/nearby galaxies in the unresolved area for SDSS to Sersic 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 and 11) using SDSS resolution are in actuality still assembling their BGGs (see Figure 4). Upon reclassifying these as progenitors and deconvolving all galaxies in the previously unresolved inner regions of our eight fossils, we find that 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 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 that this is a resolution issue in our fossil system sample, as there are fewer fossil systems than non-fossils, leading to higher uncertainties in the luminosity functions. By combining fossil and progenitors into one data set, the expected differences with non-fossils are seen.\(^6\) 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

\(^6\) 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 fit well by a Schechter function.
luminosity function due to there being a relatively small 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 \( 10^{10} < L_{\text{gal}} < 10^{11} L_\odot \) (Figure 6). While less significant than what is expected in nearby \( (z < 0.2) \) fossil systems due to the expected, rapid widening of the BGG magnitude gap at this epoch (Gozaliasl et al. 2014), this small deficit should grow as \( z \) decreases as more galaxies are cannibalized by the BGG, thus widening both the bright-end and faint-end deviations from non-fossils as fainter galaxies disappear from the population and the bright BGG increases in luminosity. We also notice that 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. Further, our lack of faint member detections worsens the already problematic issue of fitting Schechter functions to fossil systems at \( L_{\text{gal}} > 10^{11} L_\odot \) due to galaxy mergers and processing over time. Thus, it is unclear how reliable the exact values of our best-fit parameters are; however, our differential analysis seems to remain valid.

Table 3 summarizes our best-fit parameters using galaxies out to \( R_{300} \).

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 timescale 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 lookback 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 \((L^*_{\text{fossil}} = 3.3 \times 10^{10} L_\odot \) and \( L^*_{\text{non}} = 2.9 \times 10^{10} L_\odot \)) 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 rapid depletion occurs, 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 the 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 CASSOWARY 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 makes direct comparisons to \( N \)-body models more difficult.

We also begin to visually see the known \( L^* \) galaxy \((10^{10} < L_{\text{gal}} < 10^{11} L_\odot) \) deficit in member galaxies in our projected \( z = 0 \) fossils when compared to our projected \( z = 0 \) fossils.
non-fossils (Figure 7). One can take the total light in this observed $10^{10} < L_{\text{gal}} < 10^{11} L_\odot$ deficit of fossil systems and compare that to the total excess of light seen for $L_{\text{gal}} > 10^{11} L_\odot$. 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 7% of each other, supporting the idea that fossil BGGs are not simply an overluminous 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 and perhaps out of as new galaxies simultaneously fall into the group and existing galaxies can now be seen at the bright end of the luminosity function for fossils. Although slight, a factor 1.6 excess is within 7% of each other, supporting the idea that fossils are the transitional category at best, and thus our results focus on a differential analysis within this sample. Errors in the fit parameters are reported at $1\sigma$ confidence.

### Table 3

| Classification          | $\phi^*$ $\times 10^{10} L_\odot$ | $L^* \times 10^{10} L_\odot$ | $\alpha$ |
|-------------------------|-----------------------------------|-------------------------------|------------------|
| Fossil Systems          | 3.49 ± 0.08                       | 3.40 ± 0.31                   | −0.07 ± 0.04     |
| Fossil Progenitors      | 3.46 ± 0.05                       | 3.87 ± 0.23                   | −0.13 ± 0.03     |
| Non-fossils             | 4.07 ± 0.05                       | 3.55 ± 0.20                   | −0.01 ± 0.02     |
| “Fossil-like” (Fossils + Progenitors) | 3.41 ± 0.04 | 3.76 ± 0.19 | −0.13 ± 0.02 |
| $z = 0$ Fossil Systems  | 3.14 ± 0.03                       | 3.32 ± 0.14                   | −0.12 ± 0.02     |
| $z = 0$ Non-Fossils     | 3.77 ± 0.07                       | 2.97 ± 0.22                   | 0.04 ± 0.04      |

Note. The best-fit parameters of a Schechter function for each fossil category in our study. It is clear that $L^*$ appears to decrease with time for both fossils and non-fossils; however, interestingly, our projected $z = 0$ $L^*$ for lensing non-fossils is lower than the $z = 0$ lensing fossils. This is likely due to the lack of faint galaxies and the excess of bright galaxies seen in our sample worsening the fits, and the fact that our lensing systems are not representative of the population as a whole. We stress that the limited scope and specificity of this sample makes direct comparisons with previous fossil luminosity function studies difficult at best, and thus our results focus on a differential analysis within this sample. Errors in the fit parameters are reported at $1\sigma$ confidence.

**Figure 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 $1\sigma$.

**Figure 6.** The rest-frame ($z \sim 0.4$) galaxy luminosity functions for a “fossil-like” category (fossils + progenitors) and non-fossils. Although slight, a statistically significant deficit of $10^{10} < L_{\text{gal}} < 10^{11} L_\odot$ galaxies can now be seen in the “fossil-like” function, which was not previously resolved in this sample (see inset). This is, in general, expected to grow with time as more galaxies are cannibalized to brighten the BGG.
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 the mass and the BGG. What was expected to be a $\sim100$ net count 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 $7.1^{+1.3}_{-1.8}$ 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 $3.0^{+0.7}_{-0.4}$ keV at 280 kpc to $9.2^{+2.3}_{-2.2}$ 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 the mass is being affected by something outside the system. As with CSWA 26, there are currently no spectra of CSWA 28, making further investigation difficult.

5.3. 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 $4.8\sigma$, and we are able to see a significant elongation of the hot gas to the southwest of the BGG (Figure 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 $\sim45\%$ 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.

6. Summary

6.1. 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 making them brighter and hotter than what is expected for non-fossils of similar galaxy richness. Progenitors as a whole are found to be between $2\sigma$ and $9\sigma$ removed from existing X-ray scaling relations, which equate to between a 40% to 700% deviation for individual systems. These offsets could be due to progenitors having deeper dark matter potential wells (i.e., more mass) than non-fossils, leading to more retained hot gas at higher temperatures; having similar halo masses as non-fossils but being more centrally concentrated; 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 $z = 0$. Although noticeable, cannibalization alone does not explain the 2.3σ average offset observed. Further, our use of $N_{200}$ (an easily measurable quantity at these redshifts) as the method of comparison with non-fossils strongly suggests that our observed trends are real and not artifacts due to an arbitrary choice of radius, enclosed mass, etc. A test that may aid in determining how important the concentrations of our progenitors are (without deeper X-ray imaging) would be to observe the projected radial distribution of all member galaxies; however, the currently available SDSS photometric redshift errors at these distances make any statistically significant study virtually impossible. A future study would need accurate radial velocities via spectra to explore this avenue of inquiry.

We observe that our progenitors are more consistent with fossil systems than non-fossils for relations involving the hot gas temperature $T_X$ supporting the hypothesis that fossil-like systems quickly reach higher $L_X$ and $T_X$ than similarly sized non-fossils. 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 both radio and X-ray AGNs could inject a substantial amount of energy into the ICM, temporarily increasing the group’s X-ray luminosity, eventually cooling and dimming once the system relaxes into its fossil state. This process should preserve any preexisting cool cores according to hydrodynamic simulations, so it does not help address the presence of non-cool cores seen in many fossils. However, we find it curious that out of nine X-ray-detected fossil progenitors, only one (CSWA 2) houses an X-ray 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 timescales are typically longer than galaxy merger timescales. 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.

6.2. HST Conclusions

Using new HST and archival 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 fossil to progenitor status. 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 note that the reclassifying of two fossils (CSWA 4 and 11) 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 $M_*, < -19.5$ 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 ($M_*, > -18.0$), it is possible that differences between our fossils and non-fossils exist 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 in $10^{10} < L_{gal} < 10^{11} L_{\odot}$ 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 lookback time and the merger timescale 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 appear 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 require 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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