Is A2261 a Fossil Galaxy Cluster in a Transitional Dynamical State?

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Abstract

Fossil cluster A2261 is well studied, but previous studies give contradictory results on its dynamical states, such as its X-ray central entropy and magnitude gap. To improve our understanding of its dynamical state, we conduct multiband spectroscopic observations with Hectospec on the MMT, covering an area out to 5 virial radii from the cluster center, and get improved completeness and membership. Using these new data, we calculate multiple dynamical indicators, including Gaussianity, distance offset, and velocity offset. These indicators suggest that A2261 is moderately relaxed. However, a Dressler–Shectman test reveals a group candidate to the south at a projected distance that is near the virial radius and overlaps with an X-ray tail-like feature. One of the galaxies associated with that group would be sufficiently bright to reduce the fossil magnitude gap. This raises the possibility that A2261 could have recently transitioned in fossil status, if the group had previously crossed the cluster and is only now found outside. In the cluster outskirts, we see an extended feature of galaxies located on the opposite side of the cluster from the group candidate. On even larger scales, we find that this feature connects, both on the sky and in velocity space, with a long (4.4 Mpc) filamentary structure in the Sloan Digital Sky Survey data. This could support the idea that a group was fed into the cluster through the filament, temporarily breaking the fossil status and resulting in a minor merger that weakly disturbed the intracluster medium of the cluster.

Unified Astronomy Thesaurus concepts: Galaxy clusters (584); Abell clusters (9); Galaxy dynamics (591); Galaxy interactions (600)

1. Introduction

Galaxy clusters are the most massive and largest gravitationally bound systems in the universe. According to the hierarchical structure formation scenario, naturally, many gravitational interactions inside of the cluster halo bring about the formation of the brightest cluster galaxy (BCG) at the gravitational center. Over time, massive galaxies are strongly affected by dynamical friction, and the BCG continues to merge with massive galaxies. Within this simple scenario, the observed properties of galaxy clusters should reflect the history of the evolution of the cluster.

In some clusters, it is predicted that a major component of the cluster’s mass formed in an early epoch of the universe and, since then, they have passively evolved, mainly through minor mergers (e.g., Ponman et al. 1994; D’Onghia et al. 2005; Dariush et al. 2010). If we accept this simple scenario, one obvious prediction is that older and more relaxed galaxy systems will present large differences in brightness between their BCG and their cluster member galaxies, and these are known as “fossil system.” Jones et al. (2003) defined this fossil galaxy system as having a large magnitude gap, $\Delta M_{12} > 2$ (in the $r$ band), between the BCG and the second BCG within a half virial radius and with high X-ray luminosity, $L_X > 10^{42}$ erg s$^{-1}$. Fossil clusters are thought to be objects at the high-mass end of the oldest and undisturbed galaxy systems (e.g., Ponman et al. 1994; Jones et al. 2003; Cypriano et al. 2006).

The large magnitude gap feature of fossil systems has been studied extensively to determine their origins. The reason for the large magnitude gap had been thought to be the special characteristics of a fossil system’s BCG. It was expected that fossil BCGs would be more massive than other BCGs in nonfossil systems, compared to their cluster mass. However, many studies have found that the properties of fossil BCGs are, in fact, not significantly different from normal BCGs (e.g., Khosroshahi et al. 2006; La Barbera et al. 2009). Other works were focused on their member galaxies. They found that there was a lower fraction of galaxies brighter than $M^*$ magnitude in fossil systems compared to normal systems. Therefore, the main hypothesis is that $M^*$ galaxies were swallowed by BCG growth inside of galaxy groups (de Oliveira et al. 2006; Zarattini et al. 2014, 2015).

Other studies have attempted to understand if the magnitude gap between a BCG and the second-brightest galaxy is a good enough criterion to select early-formed and relaxed systems such as fossils (Dariush et al. 2010; Raouf et al. 2016). There is much debate about whether the concept of a fossil is a final stage of the dynamical state or a more transitional event by studying the magnitude gap difference (von Benda-Beckmann et al. 2008; Dariush et al. 2010; Smith et al. 2010; Zarattini et al. 2015). Von Benda-Beckmann et al. (2008) argued that whenever a galaxy system has a large magnitude gap, the difference can be updated by continuous matter infalling from the surrounding environment. Dariush et al. (2010) selected...
fossil groups at three different redshifts using simulations and traced them until $z = 0$, but none of them maintained their large magnitude gap after $\sim 4$ Gyr. Zarattini et al. (2015) showed the existence of substructures in a cluster-mass fossil system. They suggested that fossil clusters can have different origins, and the fossil condition at cluster masses is not firmly relaxed.

We select Abell 2261 (A2261) for study as a system with a contradictory dynamical state, and it may be an example of the disturbed fossil system whose origin we hope to better understand. In Kim et al. (2017), a good correlation between the magnitude gap and X-ray central entropy is found (see their Figure 2). However, in their figure, there are two outlier points, which are scattered from the main tendency. These outlier clusters have a contradictory dynamical state that high magnitude gap but with a substantial X-ray central entropy value (Cavagnolo et al. 2009). Although both are outliers, A2261 was chosen because it fulfills the conventional fossil criteria; thus, it can show a more prominent hint than the other. Using wider and more complete multiobject spectroscopic observations, we revisit A2261 to better understand its controversial dynamical state.

In Section 2, we describe our spectroscopic observations and data reduction, catalog data, and cluster member selection. We then show the results of the dynamical state of A2261 in Section 3. Using new data, we check simple dynamical indicators, do the Dressler–Shectman (D-S) test (Dressler & Shectman 1988), and compare spectroscopic membership position with X-ray data. We also test the membership probability of galaxies in the cluster by comparison with simulation data and look at filament connections with the cluster using the Sloan Digital Sky Survey (SDSS; York et al. 2000) data. In Section 4, we discuss the possible scenarios for the dynamical state of A2261 and the possibility of a transitional origin for some fossil clusters. Section 5 presents a summary of our study. In this paper, we adopt a $\Lambda$CDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$, which give a plate scale of 3.604 kpc arcsec$^{-1}$ at the redshift ($z = 0.2242$) for A2261.

2. The Data

2.1. Photometric Data

To choose targets for multiobject spectroscopy, the SDSS Data Release 12 (Alam et al. 2015) was used. The composite model magnitude ($c_{\text{ModelMag}}$) is derived from a linear combination of the exponential and de Vaucouleurs fitting method; thus, it is better than others for fitting the galaxy light profile. The model magnitude ($\text{modelMag}$) is obtained by fitting with a higher-likelihood model to measure the flux through equivalent apertures for the unbiased colors of galaxies. Thus, we used $c_{\text{ModelMag}}$ for the total magnitude and $\text{modelMag}$ for measuring galaxy colors in the following analysis. For this, we used SDSS Data Release 16 (DR16; Ahumada et al. 2020).

We used the Subaru prime focus camera (Suprime-Cam) $B_r$, $V_r$, and $R$-band ($34' \times 27'$) photometric images from the Subaru public data archive, the Subaru-Mitaka Okayama-KisoArchive System (Baba et al. 2002), to visualize the galaxy distribution of A2261 (Figure 1). We used Subaru images because they have a wider field of view and better quality than SDSS. Figure 1 is a color image within the half virial radius of A2261 (the virial radius is 1.114 Mpc, as measured from our own data; see Section 2.3) and shows the dominance of the BCG. There is no galaxy that has a similar brightness to that of the BCG ($c_{\text{ModelMag}} (r) = 15.57$ within the half virial region of the cluster, even when we see it by eye. The other physical properties of A2261 are summarized in Table 1.

2.2. Spectroscopic Data

Object A2261 is one of the clusters in the Hectospec cluster survey (HeCS; Rines et al. 2013) catalog. The HeCS has observed 58 galaxy clusters within $z = 0.1–0.3$ based on SDSS DR7 (Abazajian et al. 2009), the ROSAT All-Sky Survey (Voges et al. 1999), and the NASA/IPAC Extragalactic Database. The member clusters in the HeCS catalog were selected based on X-ray detection; thus, most clusters are massive. Candidate cluster member galaxies were selected using the red-sequence technique (Gladders & Yee 2000), so confirmed cluster members are biased toward redder colors and brighter magnitudes among all of the true members. The spectroscopy membership data for A2261 in the HeCS catalog are at $z = 0.20–0.24$ and within 1° of the cluster center. We obtain 209 spectroscopic redshifts having $r < 21$ from the catalog. These data have an average completeness of 31% within $1R_{200}$ and 20% completeness within $5R_{vir}$

Because of the low completeness of the existing data, we tried to obtain complementary data for A2261 by conducting our own observations with Hectospec (Fabricant et al. 2005) on the MMT in the observing period 2017A (Program ID: MMT-2017A-3). First, potential member galaxies were selected using photometric redshifts (Beck et al. 2016) from SDSS within a 1° field of view. Target galaxies were extracted within $z_{\text{cl}} \pm 0.0527$, which is from $\Delta z_{\text{phot}} = z_{\text{cl}} \pm (1 + z_{\text{cl}})0.043$ (0.043 is the rms of the Photo2Errclass of the SDSS), $c_{\text{ModelMag}} - \text{modelMag} < 1.7$, and $c_{\text{ModelMag}} < 22.5$. The color and magnitude cuts were chosen based on a color–magnitude diagram (CMD) of the SDSS galaxies with the HeCS confirmed members overlaid. Galaxies in the archive data were excluded from the target list. Target priority was decided based on $r$-band magnitude and distance from the cluster center. Hectospec can place 300 fibers.
simultaneously and has a 1° field of view. We assigned only 250 fibers for target galaxies because of the fiber collision problem that occurs when the distribution is very dense within a small region. Extra fibers were placed for standard stars and sky measurements. For on-source integral time, we allocated 20 minutes × 3 times (1 hr) per configuration to get a signal-to-noise ratio (S/N) >5 for a blue galaxy, which has $m_r \leq 21.5$, and an S/N > 3 for a red galaxy, which has $m_r < 20$. Two configurations were executed (2 hr).

The observed data were processed with the IDL HSRED v2 package (developed by Richard Cool) using the Hectospec data reduction program. This program provides a list of best-fit redshift values. We tried to estimate the redshift correctly by matching the RVSAO best-fit list with visual inspection data that are verified through the IDL-based spectrum visualization program, Specpro (Masters & Capak 2011). In the visual inspection, we usually used Hα, [O III], Hβ, and [O II] emission lines and Ca II H and K, Mg II, and G-band absorption lines. We classified three kinds of flags for visual inspection: “flag 1” for three lines matched, “flag 2” for two lines or uncertain cases, and “flag 3” for the zero or one-line case. The inclusion of flag 2 objects only provides 19 additional objects, and these are less trustworthy. Therefore, we decided to use only flag 1 objects in this study. After matching the best-fit list with the visual inspection data, we obtained the spectral redshifts of 371 galaxies with a redshift uncertainty of ~40 km s$^{-1}$.

Figure 2 presents the histogram and completeness of the total data sample of A2261. The completeness is calculated using galaxies having an $m_r < 20$ and 30 radius range in the SDSS photometry data. Through our observations, the total completeness is increased (see Figure 2(a)). The mean completeness within 1R$_{200}$ is increased to 45%, and the mean completeness within 5R$_{200}$ is 24%. The 2D completeness map shows a uniform distribution by decreasing with radius. In Figure 2(b), the completeness as a function of r-band magnitude is shown. The completeness reaches 50% (horizontal dashed line) at 19.3 mag with the addition of the new data. Figure 2(c) has a dominant peak between $z = 0.218$ and 0.232, which is similar to the known redshift range of A2261 from Rines et al. (2013). Dominant foreground redshift peaks are not visible, but dominant foreground redshift peaks can be seen.

### 2.3. Cluster Member Galaxy Identification

In this paper, we use the caustic method (Diaferio & Geller 1997; Serra & Diaferio 2013) to obtain the member classification and calculate new physical parameters based on the new membership. The caustic method (Diaferio & Geller 1997) identifies cluster members using the escape velocity of the cluster. The escape velocity lines from the caustic method have a trumpet-like shape. The caustic method is less severely affected by the dynamical equilibrium than traditional techniques (see Monteiro-Oliveira et al. 2022); thus, it is possible to find unrelaxed first-infaller cluster members even outside of the virial radius of the cluster. However, its success relies on having enough galaxies in the sample (~200) to detect the caustic (Serra & Diaferio 2013), a number that we easily exceed with our new spectroscopy.

We used the Caustic App v1.6 free software tool, developed by Serra & Diaferio (2013). We set it to calculate a new center position and properties of the cluster. It identified 257 galaxies as members from a total of 526 galaxies. Figure 3(a) shows the identified member galaxies of A2261 (orange circles) and indicates the calculated caustic line with error range (black dotted line and gray shading) obtained from the Caustic App.

**New properties.** We found that member galaxies are distributed out to ~5 Mpc from the cluster center with a cluster velocity dispersion of ~661 km s$^{-1}$. The new virial radius of the cluster was calculated as $R_{200} = ~1.114$ Mpc. Both velocity dispersion and $R_{200}$ are calculated using member galaxies that are inside the caustic profile and therefore can be found out to 5$R_{200}$.

The new center point had a negligible change (R.A.: 260.6129, decl.: 32.1338) from the HeCS data. This result is similar to the X-ray center position in ACCEPt (Cavagnolo et al. 2009; R.A.: 260.6135, decl.: 32.1329) and BCG position (R.A.: 260.6132, decl.: 32.1325). The projected positional offset between the new center point and the X-ray center is 13 kpc (0.012R$_{200}$), and the projected offset between the new center point and the BCG is 17 kpc (0.015R$_{200}$). The radial velocity offset between the BCG and the new center point is 245 km s$^{-1}$ (0.37σ$_{cl}$). These offset values show that the center point of the cluster and BCG are well matched, which can be considered an indicator of a cluster with a relaxed dynamical state, but the radial velocity offset shows quite a difference.

**Main features.** Figure 3(b) shows the spatial distribution of the member galaxies, nonmember galaxies, BCG, second-brightest galaxy within a half virial radius (m2$_{0.5R_{vir}}$) and whole cluster member (m2$_{all}$), and group candidate positions (all are discussed with more detail in Section 3.2). The second-brightest galaxy within a half virial radius (m2$_{0.5R_{vir}}$), second-brightest galaxy with whole cluster member (m2$_{all}$), and group candidate are highlighted on the CMD of the members (see Figure 3(c)). The entire shape of the spatial distribution of the member galaxies is elongated along the northeast direction (toward the upper left corner in panel (b)). Although we observe a 1° field of view with no directional bias (see Figure 3(b)), member galaxies (as identified by the caustic method) were found all the way out to 5R$_{vir}$ in this direction. This is far beyond the typical radius reached by backslash galaxies (Moore et al. 2004; Pimbblet 2011). This extended...
feature has a similar velocity dispersion as the cluster value. We suspect this is evidence of a nearby filament that is connected with A2261, and we find further evidence for this picture in Section 3.5.

**CMD.** The CMD is also shown in panel (c). To make this diagram, the SDSS model $g$ and $r$ magnitudes are used for our spectroscopically confirmed members. We limit our sample to galaxies out to $3R_{\text{vir}}$ from the cluster center to exclude possible filament galaxies but not neglect possible backsplash galaxies. In the conventional definition of a fossil system, the second-brightest galaxy must be within $0.5R_{\text{vir}}$ and at least 2 mag fainter than the BCG. As shown in Figure 3(c), the pink circles, which represent galaxies inside $0.5R_{\text{vir}}$, are all 2 mag fainter, meaning A2261 should indeed be classified as a fossil system. We label the brightest galaxy among them as $m2_{0.5R_{\text{vir}}}$, as it is the second-brightest galaxy to the BCG inside of $0.5R_{\text{vir}}$ (indicated with a green triangle).

Besides, we can also find another bright galaxy. This is located just beyond the virial radius of the cluster ($\sim 1.27R_{\text{vir}}$, $\sim 1.41$ Mpc), is actually brighter than $m2_{0.5R_{\text{vir}}}$, and has a magnitude gap of less than 2 mag ($\Delta M_{\text{g}} = 1.49$) with the BCG. This is less than the fossil magnitude gap criteria (Figure 3(c)), but because it is beyond the virial radius, it does not break the fossil definition. Because this galaxy is the second-brightest galaxy compared to the BCG of all of our cluster members, we hereafter label it $m2_{\text{all}}$. We also investigate its features in more detail in Section 3.3.

### 3. Results

Using our new membership galaxy data, we wish to measure the dynamical state throughout the cluster, from its core to its outskirts. First, we check the values of the dynamical state indicators using our spectroscopic data in Section 3.1. In Section 3.2, we use the D-S test to search for substructures. We also compare with X-ray emission contours in Section 3.3. The probability of the presented group candidate is checked in Section 3.4, and the presence of a nearby large-scale structure is confirmed in Section 3.5.

#### 3.1. Dynamical Indicators

Here we measure various dynamical state indicators for A2261, as listed individually below. We compare these measurements to the same measurements for a comparison sample of clusters. To build the comparison sample, we begin with 212 spectroscopically observed galaxy clusters from the Cluster Infall Regions in SDSS (Rines & Diaferio 2006; 72), HeCS (58), the Hectospec Cluster Survey of SZ-selected clusters (Rines et al. 2016; 53), the Hectospec Cluster Survey of red sequence-selected clusters (Rines et al. 2018; 23) project catalogs, and others (Hwang et al. 2014, six) clusters. Those include massive and X-ray-detected clusters within $z = 0.001-0.29$. Among them, we choose 106 galaxy clusters for our comparison sample that have up to 70% spectroscopic completeness. The minimum, maximum, and average number of member galaxies of 106 clusters are 16, 1349, and 205, respectively. Figure 4 shows histograms of each type of dynamical state indicator of the 106 galaxy clusters. Insets in each panel are the normalized cumulative fraction of each indicator. In this way, we can compare the dynamical state of A2261 (shown with a black arrow) to that of the comparison sample, measured in the same way.

**Gaussianity.** The kurtosis and skewness are used to check the Gaussianity of the velocity distribution of the cluster members (Pinkney et al. 1996; Hwang & Lee 2007; Einasto...
et al. 2012). The kurtosis values in this figure are given as the difference with respect to the Gaussian value of 3. Thus, the direction along the x-axis toward a value of zero means a more Gaussian distribution. The Gaussianity of the velocity distribution of the cluster can be interpreted as a measure of the orbital relaxation of the member galaxies, as large numbers of first infallers could make the distribution increasingly non-Gaussian. Also, if there is a significant substructure or the cluster is merging, the non-Gaussianity would increase further.

The calculated values of skewness and kurtosis are 0.056 and −0.63, respectively. This means that A2261 is skewed a little left and has a slightly peaked central distribution. We also see the location of the value of A2261 in the histogram of sample galaxy clusters and do a Shapiro–Wilk normality test (Shapiro & Wilk 1965), which is usually proper for samples of a small size. We get a p-value from the Shapiro–Wilk test of $P_{SW} = 0.044$, which indicates that A2261 has a velocity distribution that deviates from a normal distribution (i.e., it is not Gaussian in shape).

Offsets. Offset indicators have been frequently used as dynamical state indicators in the past, with small offsets tending to indicate a more relaxed state. However, the value of measured offset parameters can be susceptible to projection effects. There are various kinds of offset parameters, and some are measured from the luminosity-weighted or X-ray center (Maughan et al. 2008; Raouf et al. 2016; Kim et al. 2017) of the cluster. In this section, we consider two offset parameters. The distance offset is the calculated difference between the luminosity-weighted center of the cluster and the BCG. For the luminosity weighting, we use the Petrosian r magnitude from SDSS DR16 that is provided by the above catalogs (there is little difference if we use cModelMag instead). When we calculate luminosity weights, the BCG magnitude is excluded from the calculation. Thus, the luminosity-weighted center represents the center among satellite member galaxies. The distance offset value is normalized by $R_{\text{vir}} (D_{\text{norm}})$. The velocity offset is measured in a similar way, only considering velocity differences instead of position differences (i.e., comparing the BCG velocity to the luminosity-weighted mean velocity of the satellite members) and normalized by the $\sigma_{\text{vir}}$ of each cluster ($V_{\text{norm}}$). There is not an exact value for dividing relaxed and unrelaxed clusters, but there are many studies that demonstrate that a small offset means a more relaxed state (Zhang et al. 2011; Raouf et al. 2019). If we assume that a value of less than 10% of the normalized value ($<0.1$) would be a relaxed system, then the distance offset of A2261 is a relaxed value, but the velocity offset is a more moderate value.

Magnitude gap and X-ray central entropy. The magnitude gap is calculated using galaxies within 0.5$R_{\text{vir}}$ after double-checking the BCG in the CMD of each cluster. As we mentioned before, conventionally, $\Delta M_{12} > 2$ is considered to be a relaxed state (e.g., Jones et al. 2003). The X-ray central entropy, $K_0$, values are from 241 galaxy clusters in ACCEPT (Cavagnolo et al. 2009); normally, lower than 30 keV cm$^2$ is considered a relaxed state (e.g., Barnes et al. 2018). For A2261, the magnitude gap is larger than the criterion, and the X-ray central entropy has a moderate value.

Considering the above indicators, most of the values of A2261 are biased toward relaxed (or Gaussian) states. The individual values of A2261 about dynamical indicators can be found in Table 2.

3.2. D-S Test

The existence of substructure is often used as a proxy of the unrelaxed state of the cluster (see Smith & Taylor 2008; Smith et al. 2010). There are many methods to find substructures inside a cluster. One of the methods, the D-S test (Dressler & Shectman 1988), is applied to our A2261 spectroscopic sample in this study.

To identify substructures, the D-S test compares the differences of the mean velocity and velocity dispersion between a global value (using all cluster galaxies) and a local value (specified number of its nearest galaxies).

First, we calculate the mean velocity and velocity dispersion for all cluster members, which is represented as $\bar{V}$ and $\sigma^2$.

Then, we calculate the mean velocity ($\bar{V}_{\text{local}}$) and velocity dispersion ($\sigma^2_{\text{local}}$) of the subcluster candidate galaxies, which

![Figure 3](image-url)
are the neighbor galaxies around the $i$th galaxy, following

$$v_{\text{local}}^i = \frac{N_n}{\sum_{j=1}^{N_n} \frac{1}{1 + z_{\text{cl}}}} \cdot c(z_j - z_{\text{cl}})$$

(1)

$$\sigma_{\text{local}}^i = \sqrt{\frac{N_n}{\sum_{j=1}^{N_n} \frac{1}{1 + z_{\text{cl}}}} (c z_j - v_{\text{cl}}^i)^2}$$

(2)

where $z_j$ is the redshift of the $j$th closest galaxy to the $i$th galaxy ($i$ for all cluster members, $j$ for subcluster galaxies), $z_{\text{cl}}$ is the $i$th galaxy itself, $N$ is the number of member galaxies, $N_n$ is the number of candidate member galaxies for a subcluster, and $N_n = \sqrt{N}$ is adapted from Pinkney et al. (1996). For A2261, $N_n = 16$ is selected. We also tested $N_n = 11$, which is the original number from Dressler & Shectman (1988), but it did not significantly change our results.

Finally, the deviation ($\delta_i^2$) of each local value from the global value is defined by

$$\delta_i^2 = \left( \frac{N_n}{\sigma_{\text{cl}}^2} \right) [ (v_{\text{local}}^i - v_{\text{cl}})^2 + (\sigma_{\text{local}}^i - \sigma_{\text{cl}})^2 ].$$  

(3)

If the mean velocity and velocity dispersion of the subcluster candidate are highly different from the cluster, the deviation value increases. We visually represent the calculated deviations with a circle whose size is proportional to $e_i$ in Figure 5, which is known as "a bubble plot."

If galaxies are gravitationally bound to each other and form a substructure, those galaxies should have a similar velocity and velocity dispersion as other galaxies near their location. Therefore, large aperture circles located close together or...
overlapping in the bubble plot can be considered as probable substructures.

Specific membership. One of the weaknesses of the D-S test is that it cannot distinguish which specific galaxy is a group member. In the literature, there are some attempts to roughly define the membership of individual galaxies using \( \delta \) values as a threshold (Bravo-Alfaro et al. 2009; Jaffé et al. 2013). A value of \( \delta > 2 \) has been used to approximately define the location of groups.

Applying this criterion to our results, the colored circles in Figure 5(a) show the probable locations of substructures. Each separated substructure is colored differently. Near the \( \sim R_{\text{vir}} \) location, there are substructures in the east (orange circles), west (pink circles), and south (green circles). In the phase-space diagram, the east (orange) and west (pink) circles have different velocities compared with nearby galaxies and are located far away from each other. Those are less likely to be genuine substructures and are perhaps just projection effects. However, the southern green circles are located near each other and have a similar size.

We also double-checked the southern green circles in the phase-space diagram (see Figure 5(c)), spatial distribution, and CMD (see Figure 3) and indicated it as “group candidate.”

On the northeast side, there are two groups of colored circles that show interesting features. The upper circles (purple) have a scattered distribution, but some of the lower circles (cyan) are well aligned and overlapped in the phase-space diagram (Figure 5(c)). This group-like feature was not detected in the previous archive data and is only revealed when we add our new observation data (see Figure 5(b)). We also tested with a different number of Local Group membership, but this substructure remains visible. This likely suggests that we have detected a group of galaxies in the cluster outskirts near \( 4R_{\text{vir}} \) that is being fed into the cluster along a connected filament.

Cumulative deviation (\( \Delta \)). As another test for the existence of substructure, we compare the cumulative deviation, \( \Delta \), values of A2261 to the cumulative deviation distribution of random distributions that have an equal sample size. The \( \Delta \) is defined by

\[
\Delta = \sum_{i=1}^{N} \delta_i,
\]

where \( N \) is the total number of member galaxies that are found beneath the caustic (see Section 2.3).

We compare this with randomly generated cumulative deviations. We generate 100,000 random distribution data sets by shuffling the velocities of the original data. Then we calculate the \( p \)-value of the observed value to the randomly generated sets (see Figure 6):

\[
P = \sum (\Delta_{\text{random}} > \Delta_{\text{original}}) / N_{\text{random}},
\]

where \( N_{\text{random}} \) is 100,000. The \( \Delta_{\text{random}} \) and \( \Delta_{\text{original}} \) are measured from the random distribution (made by shuffling the velocities) and the original distribution of A2261, respectively. The mean value of the random sets (\( \Delta_{\text{random}} \)) is 169.3 with a standard deviation of 20.4. The original cumulative deviation from the original distribution (\( \Delta_{\text{original}} \)) is 249.4, which is 3\( \sigma \) above. Thus, the observed cumulative deviation is 3\( \sigma \) above the mean value of the randomly generated sets (a \( p \)-value \( \leq 0.01 \)). This means the original distribution is unlikely to be a random distribution with a high significance. Physically, this can be interpreted as meaning that substructure exists in the A2261 members with a high probability, which could be considered a
feature of an unrelaxed cluster. If we exclude galaxies beyond 1 $R_{\text{vir}}$, the original distribution is $2\sigma$ above.

3.3. The Group Candidate in X-Rays

To follow up on the possible group candidates from the D-S test, we also studied the X-ray observations of A2261. We used the X-ray surface brightness contour profile from Maughan et al. (2008). These X-ray data are from the Chandra Advanced CCD Imaging Spectrometer observation (ObsID 5007) in 2004. The contour map is available on their website.\(^8\)

Figure 7 shows an image with a smoothed X-ray emission contour and our spectroscopic member galaxies on the Subaru $R_c$-band optical image of A2261. The strength of the X-ray emission decreases with radius, and the overall shapes are well ordered.

However, there are a few clumps visible in the contours. Savini et al. (2019) tested whether the western clump might be an infalling group, but they ruled this out. At its location, they found a background red galaxy at $z = 0.236$, slightly beyond the cluster membership redshift range ($0.2165 < \Delta < 0.2321$). There are also a foreground galaxy (photometric redshift = 0.088; Csabai et al. 2007) and a star, all located very close to each other in the sky. But there is neither a galaxy group nor a host of a hot gas clump, such as an active galactic nucleus (AGN), QSO, or radio galaxy. The spectra of the galaxies also do not show any significant broad emission lines to be detected as AGN, QSO, or radio galaxies.

Only the X-ray clump located toward the south matches the spectroscopically confirmed member location. There are five member galaxies with absorption line features. Among nearby galaxies, three are matched with the location of the high-deviation assembled circles at the D-S test (Figure 7(b)) and the group candidate location on the caustic profile (Figure 3(a)). This provides further confirmation of the presence of a real substructure in the southern part of A2261. Furthermore, the tail-like shape of the X-ray contours centered on the group gives the impression that the group is interacting with the cluster’s intracluster medium. The direction of the X-ray tail points roughly inward, as if the group is exiting the cluster, although we cannot be certain of the influence of projection effects.

Interestingly, one of the members in the X-ray clump is m2_all, which has a brighter magnitude value than m2_0.5$R_{\text{vir}}$. Here m2_all is sufficiently bright that it would break the fossil definition if it were inside the half virial radius ($m_{\text{BCG}} - m_{\text{all}} = 1.49$), but it is currently found beyond the virial radius. Therefore, assuming the group previously crossed the cluster in the past, here we attempt to estimate timescales for the cluster to transition from its fossil status. To do this, we must make many simplifying assumptions.

We do not know the true orbital velocity of the group candidate. We can only measure its line-of-sight velocity. If we assume that the average velocity of the group candidate is similar to the 3D cluster velocity dispersion, and that the cluster has an isotropic velocity distribution, then its 3D velocity is $\sqrt{3} \times 661$ km s$^{-1} = 1145$ km s$^{-1} = 1.145$ Mpc Gyr$^{-1}$. Now we estimate how long it would take for the group to cross from entering the half virial radius of the cluster on the opposite side until reaching the half virial radius on its current side of the cluster. We find that this would take about $\sim 0.97$ Gyr in total. During this time, A2261 would cease to be a fossil system, only transitioning back to being a fossil when the group leaves the half virial radius on the southwest side.

We now estimate how long it would take, after leaving the half virial radius, to reach its currently observed position. This is the amount of time that the cluster has been a fossil system since the transition. We do not know the true separation between cluster and group (in three dimensions). If we assume spherical symmetry for the group projected distance, the average expected 3D separation between the group and the cluster center is $\pi/2 \times 1.35$ Mpc = 2.12 Mpc. The time required for the group to go from 2.12 Mpc to half the virial radius is $(2.12-0.55)/1.145$ Mpc Gyr$^{-1}$ = 1.36 Gyr, or, if the projected distance is the true distance, 0.8 Gyr.

Under this assumption, the timescales mean that the cluster will remain as a fossil for another 0.8 (assuming the true separation distance is equal to the projected distance) or $\sim 1.36$ (assuming the true separation distance is the 3D distance) Gyrs, at which point it will enter the half virial radius and break the fossil definition.

In summary, we estimate that the presence of the group containing m2_all likely causes A2261 to transition between fossil and nonfossil status on timescales of roughly a gigayear.

3.4. Cluster Member Probability of Group Candidate

Projection effects can make a target seem closer to the cluster than it really is. Thus, we try to apply projected phase-space diagrams using dark matter halos near massive host halos from the Illustris-TNG simulation data (Pillepich et al. 2018; Springel et al. 2018).

**Membership probability plot within 3$R_{\text{vir}}$.** We chose 1566 massive host halos having $M_{\text{vir}} \geq 10^{13}$ $M_{\odot}$ and all subhalos having $M_{\text{vir}} \geq 10^{11}$ $M_{\odot}$. The projected distance and velocity of all halos are normalized by virial radius and the velocity dispersion of each nearby cluster halo in the projected phase-space plane. We calculate the probability that a halo is truly

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\(^8\) http://exc.cfa.harvard.edu/cda/Contribution/2007/MAUG1
within $3R_{\text{vir}}$ of the cluster ($p_{3r}$) at each location in the projected phase space. This is calculated by taking the number of halos within $3R_{\text{vir}}$ ($n_{3r}$) divided by the total number of galaxies ($n_{\text{total}}$), including interlopers within specific pixels of the projected phase-space plot:

$$p_{3r} = \frac{n_{3r}}{n_{\text{total}}}. \quad (6)$$

As we can see in Figure 8, low-to-high probability is represented by the colors (see color bar). At the BCG, the probability is nearly 100% member, and $m2_{0.5R_{\text{vir}}}$ is $\sim 90\%$. The $m2_{\text{all}}$ and substructure candidate are at $60\%$--$70\%$ member probability position. This demonstrates that the substructure detected to the south of the cluster has a high probability of being genuinely near the cluster from its phase-space location alone. The fact that its X-ray emission appears to be interacting with the cluster strengthens the idea that the substructure is located in the cluster outskirts and not simply projected onto the cluster.

**Regions in phase space.** We also try to interpret their phase-space locations using the approach of splitting up the regions, as shown in Rhee et al. (2017). In Figure 6 of that study, which is a schematic distribution diagram (without error), they divide the galaxies into four types by their “time since infall ($t_{\text{inf}}$)” and look at the breakdown of these types in each region of a projected phase-space diagram (or radius-velocity, R-V, diagram). As galaxies fall into the cluster from outside, they typically tend to follow a track that is from region A through to region E in alphabetical order. As a result, “first infallers” dominate in region A, “recent infallers” ($0 \text{ Gyr} < t_{\text{inf}} < \sim 3.63 \text{ Gyr}$) dominate in regions B and C, “intermediate infallers” ($3.63 \text{ Gyr} < t_{\text{inf}} < \sim 6.45 \text{ Gyr}$) dominate in region D, and “ancient infallers” ($6.45 \text{ Gyr} < t_{\text{inf}} < \sim 13.7 \text{ Gyr}$) dominate in region E.

The BCG and $m2_{0.5R_{\text{vir}}}$ fall in region E, which is the region most dominated by ancient infallers. The $m2_{\text{all}}$ and substructure candidates both fall on the border of region D, which is the region most dominated by intermediate infallers.

If there was a minor merger between the cluster and the group that includes $m2_{\text{all}}$, this amount of time would be enough to relax the optical parameter change (e.g., the magnitude gap; Dariush et al. 2010; Kundert et al. 2017) of the cluster, but it is likely not enough time for the disturbed X-ray parameters to cool down (Ettori & Brighenti 2008).

The results from previous sections and this result point to a simple scenario: A2261 may have experienced a past minor merger with a group, the group has since passed through the cluster (having fallen in at least 3.63 Gyr ago), and it is now located in the backsplash region.
3.5. Nearby Large-scale Structure Environment around A2261

From previous sections, we can expect that the group candidate has previously penetrated the intracluster medium of A2261. Furthermore, the group candidate is likely located in the cluster outskirts and is not a virialized member of the cluster. The member galaxy distribution is stretched to the northeast side of A2261 if a filament was connected to the cluster there, and there is evidence for a group infalling within the filament (or a minor merger). In this section, we consider the structure on larger scales around the cluster.

In the total distribution in Figure 9(a), the background completeness of the SDSS DR16 spectroscopy observation shows diagonal strips (running from bottom left to top right) due to the manner in which the sky was mapped. If we focus on the green circles, which show galaxies with similar velocities to the cluster, we can see a possible filamentary feature. It emerges from the extended feature of a cluster and continues toward the top left side, following the direction indicated by the black arrow.

We note that the completeness of the area where the green circles appear to align along a possible filament is not higher in that direction. The possible filament lies perpendicular to the enhanced completeness diagonal strip features. This means the possible filament feature is unlikely to be an effect of varying completeness. In panel (b), the R-V diagram of the northeast region shows that the galaxies in the possible filament (as seen on the sky) have similar velocities and lie roughly on the plane of the sky over a large range of radii. Most of the galaxies in the northeast region are located within $\pm 2000$ km s$^{-1}$ velocity dispersion, and the feature seems to be directly connected with the cluster on the northeast side both spatially and kinematically.

Furthermore, as we saw in Figure 3(b), the location where the possible filament reaches the cluster is the same as the location of the extended feature seen in our own A2261 data. This is further support for a filament that connects with the cluster on the northeast side. We see only a small gradual velocity increase with increasing distance along the filament as shown.

Environment. We also looked for the presence of previously known groups and clusters in the vicinity of A2261. Fossil systems are thought to live in sparse environments if passive evolution is behind the origin of the high magnitude gap.

Pink plus signs show nearby cluster locations from the MCXC catalog (Piffaretti et al. 2011), but all are farther than $\pm 8000$ km s$^{-1}$ recessional velocity from A2261. Unfortunately, MCXC clusters have only larger mass than average cluster mass, because of the limitation of X-ray observation, and so the presence of group-scale objects cannot be ruled out. Although it appears that there are no cluster-mass neighbors within the $6^\circ \times 6^\circ$ range, our results suggest that there are nearby groups like the A2261 group candidates. For example, in Figure 3(c), there is a prominent candidate of a group at redshift 0.21. We note that the SDSS data are sharply cut in the lower left corner of Figure 9(a) because it is not observed in SDSS, but fortunately, this does not affect the area of interest around the possible filament feature.

It is interesting to note that the group candidate (blue square in Figure 9(a)) is roughly on the opposite side from the filament feature. It is well known that filaments form conduits by which groups enter clusters. Therefore, it is possible that this group entered the cluster from the filament and crossed the cluster, emerging on the south side, where it is observed.

Figure 9. (a) Nearby large-scale structure in a $6^\circ \times 6^\circ$ range (roughly $\sim 60$ Mpc$^2$ scale) about A2261. The gray-scale color bar shows completeness. Background mosaics show the SDSS spectroscopic completeness on the sky plane. The red, green, and blue circles are galaxies within $8000$ km s$^{-1} \gtrsim v \gtrsim 2000$ km s$^{-1}$, $2000$ km s$^{-1} \gtrsim v \gtrsim -2000$ km s$^{-1}$, and $-2000$ km s$^{-1} \gtrsim v \gtrsim -8000$ km s$^{-1}$, respectively (based on SDSS spectroscopy). Black circles indicate the cluster members from our main spectroscopic data sample. A pink arrow indicates the most probable direction of a filament that connects with the cluster. A blue square shows the location of the group candidate. The pink box shows the northeast region. The pink plus signs are cluster locations around A2261. (b) Phase-space diagram of the northeast region. The red dashed line shows the $\sim 1R_{200}$ region. The shaded region is $\pm 2000$ km s$^{-1}$ of the cluster radial velocity. All color-coding is the same as in panel (a).
4. Discussion

In this section, we discuss how our results on the dynamical state of A2261 fit in with previous multiwavelength studies of A2261 and the fossil origin controversy of whether fossils are transitional or not.

4.1. Comparison with Previous Studies about the Dynamical State of A2261

In previous research, there were contradictory results about the dynamical state of A2261. Some consider it a relaxed system (e.g., Maughan et al. 2008; Mann & Ebeling 2012; Landry et al. 2013; Wen & Han 2013; Rumsey et al. 2016; Harvey et al. 2017). Others argue that it is disturbed system (e.g., Gilmour et al. 2009; Savini et al. 2019). Here we summarized studies about weak lensing, strong lensing, and radio and X-ray analysis of the dynamical state of A2261.

The weak and strong lensing studies show the dark matter distribution of A2261 and calculate an accurate mass concentration parameter. Normally, a stable system is expected to have a high mass concentration parameter, and this is also considered to be evidence of early formation (see Wechsler et al. 2002; Umetu et al. 2009) because the concentration of dark matter halos evolves with time. By calculating the formation time, Coe et al. (2012) hypothesized that A2261 has not finished forming and is a borderline relaxed and cool-core system.

In a recent radio paper, Savini et al. (2019) reported a large diffuse radio halo at about 500 kpc on the northwest side of the A2261 center. Usually, the radio halo is believed to be formed by a major merger, but A2261 is considered to be a nonmajor merger radio halo from the well-ordered X-ray emission contour. If it had a merger before, the X-ray emission contour is expected to be misaligned, because the hot gas of the cluster is disturbed by the infalling matter.

For the X-ray parameters, previous studies divide clusters into different dynamical states based on their X-ray central entropy, with 30 keV cm$^2$ being the dividing line. Lower than 30 keV cm$^2$ is categorized as a cool-core system and larger than 30 keV cm$^2$ as a non-cool-core system. However, actively merging clusters have up to 100 keV cm$^2$ entropy values. Object A2261 has a moderate X-ray central entropy value, $K_0$(central entropy) = 61.08 keV cm$^2$ (Cavagnolo et al. 2009), which is an abnormally high value for a relaxed cluster.

Sommer et al. (2017) argued that they could not find a prominent merger sign. The moderate X-ray entropy feature could indicate a minor off-axis merger. Rumsey et al. (2016) hypothesized that A2261 could be at the beginning of a high mass ratio merger before the first pericenter using their results of low X-ray temperature and Sunyaev–Zeldovich effect and other X-ray parameters.

Summing up the previous results, most studies conclude that the formation of A2261 might not yet be complete, and some studies suggest that it is undergoing an off-axis minor merger. An off-axis minor merger could simultaneously explain both the moderately enhanced X-ray entropy value and the well-organized shape of the X-ray contour.

We propose that the clump in the southern part of the cluster center, detected by X-ray and radio wavelengths, could be a good candidate for the perturbing galaxy group. We detect this group with our spectroscopic data using a D-S test. Our study also agrees well with previous results on the dynamical state of the cluster. We speculate that one reason for the contradictory dynamical state of A2261 is the off-axis minor merger, which would cause only weak changes in the dynamical state parameters.

Given that the brightest group galaxy (m2_all) is similar to the mass of the BCG, what is needed for the present dynamical state of A2261 is that the previous merger has to have an off-axis orbit. If an on-axis merger occurred, we might expect it to heavily disturb the BGG by the strong tidal interaction of the two massive galaxies. However, when we check the optical morphology of the BCG and m2_all, we do not find any optical features (such as tidal disturbances or merger features) to support this. Some studies report that A2261 has a flat core structure (Postman et al. 2012) and four stellar knots inside (Burke-Spolaor et al. 2017) that could be interpreted as boxy isophotes. However, these features were likely made from a much earlier major merger that fully coalesced during the early cluster formation, rather than the recent minor group passage we consider here. Also, if it is past the center of the cluster, the group has to be broken (Benavides et al. 2020).

4.2. What Does A2261 Tell Us about Possible Transitional State Fossils?

There is much competing evidence on each side for observed fossil origins, either due to “real physics” or as “by chance (transitional)” objects.

First, the “by chance” camp argues that fossils and nonfossils have the same BCG parameters (Khosroshahi et al. 2006; La Barbera et al. 2009), scaling relation (Khosroshahi & Ponman 2007), size–luminosity relation, fundamental plane, Faber–Jackson relation (Méndez-Abreu et al. 2012), absence of large gradient in the metallicity of the BCG (Eigenthaler & Zeilinger 2013), similar amount of substructure (Zarattini et al. 2016), and environment (Pierini et al. 2011; Adami et al. 2012). They argue that these same physical properties mean the same formation sequence as in nonfossil systems.

In particular, the claim of Eigenthaler & Zeilinger (2013) is critical. A monotonic collapse of the BGG is expected to make a steep metallicity gradient, and only major mergers are able to make a flattened metallicity gradient. As a result, a BCG in a fossil cluster should not be able to maintain a high metallicity gradient if there were multiple mergers of $L^+*$ galaxies before $z = 1$. However, their six fossil central galaxies showed flat metallicity gradients. In addition, Proctor et al. (2014) showed two fossil groups with differing star formation histories, even though both shared similar optical properties and kinematics.

Next, the “real” camp asserts that the BCGs of fossil systems have more boxy isophotes (Khosroshahi et al. 2006), more sparse environments (closer to filament than node; Adami et al. 2020), less bright characteristic magnitude ($M^*$; Zarattini et al. 2015), heavier halo masses (Dariush et al. 2007), lower dwarf galaxy fractions in their luminosity functions (Gozalís et al. 2014), more radial orbit (Zarattini et al. 2021), and different assembly bias (Li & Cen 2020) than nonfossil systems.

Usually, the boxy isophote of a BCG is considered as evidence of a past major merger. This fits with the $L^+$ merger hypothesis to explain the fossil BCG formation. Sparse environments support the passive evolution of the fossil system. Other differences support that a specific process occurred to form the high magnitude gap, and that the abovementioned features cannot be explained as “coincidental results.”
For A2261, we search for the abovementioned features in the literature and catalogs. The BCG of A2261 indeed has a flat core, which can be interpreted as a boxy shape (Burke-Spolaor et al. 2017). Also, it is well known as a black hole–black hole merger candidate (Burke-Spolaor et al. 2017); thus, it is usually assumed to have suffered a merger in the past. The X-ray spectral metallicity of A2261’s BCG shows a steep decrease within 30 kpc. Beyond that, it becomes flatter until about a 300 kpc radius (Gültekin et al. 2021). Except for the central part, its metallicity appears to be in quite a mixed state. In the optical luminosity function, A2261 has a less bright $M_*$ and a flatter faint-end slope $\alpha$ (Barrena et al. 2012; even though they distinguished A2261 as a disturbed sample, its $M_*$ and $\alpha$ values are more similar to a relaxed sample). The sparse environment of A2261 is shown in this paper (see Section 3.5). Therefore, although A2261’s BCG has likely suffered a recent off-axis minor merger, its total structure formation is similar to real fossil formation physics.

Even though we believe that A2261 is likely a transitional fossil cluster, we cannot determine that all fossils are transitional using our result. However, we can suppose that a fraction of fossil systems like A2261 might be contaminated samples of pure fossil systems.

5. Summary

In this study, we attempt to determine the dynamical state of the fossil cluster Abell 2261 (A2261) using our own spectroscopic observations taken with the Hectospec at the MMT to complement existing data in the literature. From previous studies of a sample of transitional fossil systems, A2261 is known to have a controversial dynamical state.

We acquired line-of-sight velocities to 373 new galaxies in the field around A2261 and identified 257 member galaxies, thus improving the spectroscopic completeness within 5$R_{\text{vir}}$ of the cluster center.

Using the spectroscopic data set, we measured multiple dynamical state indicators, such as Gaussianity and luminosity-weighted offset indicators, and we found that A2261 generally falls on the relaxed side of the distributions of clusters in our comparison sample.

However, a D-S test confirms with a high significance that substructure exists. One of the probable substructures is located to the south of the cluster, just beyond the virial radius. An X-ray emission map highlights that hot gas is associated with this substructure and has a comet-like shape, as if the substructure is interacting with the cluster’s hot gas, with a tail pointing toward the cluster. The location of the substructure is well matched with a bright spectroscopically confirmed member galaxy, $m_{2\text{-all}}$, whose luminosity is within 2 mag of the cluster BCG. A phase-space analysis suggests that it is likely located in the cluster outskirts, between 1 and 3 virial radii. At its current location, it does not break the fossil criteria, but if it had previously crossed the cluster or later falls into the cluster, A2261 would transition to being a nonfossil.

Toward the northeast of the cluster, we detect an extended feature of member galaxies out to 5 virial radii from the cluster that resembles a filament connected to the cluster. Thanks to the addition of our new spectroscopic data, a D-S test reveals a probable substructure within the filament, located at a projected distance of 4$R_{\text{vir}}$ from the cluster center. This likely indicates that a group is being fed into the cluster along the filament.

Using the available SDSS spectroscopy, we checked the large-scale structure in the surroundings of A2261 until 30$R_{\text{vir}}$. We find that the extended feature seen in the Hectospec data becomes a filamentary-like feature of SDSS galaxies on much larger scales ($\sim 15$ Mpc) that connects with the cluster both in position and in velocity space.

Given that the confirmed substructure to the south is roughly on the opposite side of the cluster from the filament, this raises the possibility that the substructure may have originally been fed into the cluster along the filament and since crossed the cluster, resulting in an off-axis minor merger, with the group currently being found in the back splash regions of the cluster today. An off-axis minor merger could explain why many of the dynamical state indicators in this study and previous studies suggest that the cluster dynamical state is between relaxed and mildly disturbed.

Therefore, we suggest that A2261 is in the moderate transitional phase. If the group crossed the cluster, A2261 may have transited from fossil to nonfossil (during the passage of the group across the cluster center on timescales lasting $\sim 1 \text{ Gyr}$) and back to fossil (from the moment of transition until now on $\sim \text{ gigayear timescales}$). In the future, it will likely return to being nonfossil when the group falls back into the cluster on similar timescales. This future transition will likely occur even if the group is in fact on first infall.

While the study of one system cannot drive broad conclusions on fossil systems as a whole, we suggest that the conventional fossil definition likely includes other transitional systems like A2261 that pollute samples of true, pure, highly relaxed fossil systems.

Therefore, we suggest the need for a moderate classification to represent transitional phase fossils, rather than a dichotomy classification. Different dynamical state indicators likely become perturbed at different stages of an ongoing merger and remain perturbed for differing amounts of time. We will study this using numerical simulation in the near future and use the results to give increased knowledge on the recent merger history of observed clusters and better identify fossil systems that could be in transition.

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