Ultradiffuse Galaxies in the Coma Cluster: Probing Their Origin and AGN Occupation Fraction

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Abstract

Ultradiffuse galaxies (UDGs) exhibit low surface brightness, but their optical extent is comparable to that of Milky Way-type galaxies. In this work, we utilize Chandra X-ray observations of 404 UDGs in the Coma cluster and address two crucial goals. First, we constrain the formation scenario of UDGs by probing the X-ray emission originating from diffuse gas and from the population of unresolved low-mass X-ray binaries (LMXBs) residing in globular clusters (GCs). It is expected that both the luminosity of the hot gas and the number of GCs, and hence the luminosity from GC-LMXBs, are proportional to the total mass of the dark matter halo. We do not detect statistically significant emission from the hot gas or from GC-LMXBs. The upper limits on the X-ray luminosities suggest that the bulk of the UDGs reside in low-mass dark matter halos, implying that they are genuine dwarf galaxies. This conclusion agrees with our previous results obtained for isolated UDGs, arguing that UDGs are a homogeneous population of galaxies. Second, we constrain the AGN occupation fraction of UDGs, i.e., the fraction of UDGs that are occupied by an active galactic nucleus, for the first time. To this end, we cross-correlate the position of detected X-ray sources in the Coma cluster with the position of UDGs. We identify two UDGs that have a luminous X-ray source at 3σ and 3σ/2 from their center, which could be off-center AGNs. However, Monte Carlo simulations suggest that one of these sources could be the result of spatial coincidence with a background AGN. Therefore, we place an upper limit of $\lesssim 0.5\%$ on the AGN occupation fraction of UDGs.

Unified Astronomy Thesaurus concepts: X-ray photometry (1820); Coma Cluster (270); Dwarf galaxies (416); Galaxy evolution (594); Low surface brightness galaxies (940)

1. Introduction

Ultradiffuse galaxies (UDGs) are a curious population of galaxies that have extremely low central surface brightness ($\mu_0(g) \gtrsim 24$ mag arcsec$^{-2}$), but large effective radii ($r_{\text{eff}} \gtrsim 1.5$ kpc). Although these galaxies were known for decades as low-surface-brightness galaxies or low-mass cluster galaxies (e.g., Sandage & Binggeli 1984; Impey et al. 1988; Conselice et al. 2003), recent observational studies rediscovered (and renamed) them. Most notably, the Dragonfly Telephoto Array (Abraham & van Dokkum 2014), which was specifically designed to resolve structures at low surface brightness levels, detected a large population of UDGs in a galaxy cluster (van Dokkum et al. 2015a). This discovery was followed by searches for UDGs in other environments (e.g., Mihos et al. 2015; Martínez-Delgado et al. 2016; Merritt et al. 2016; Bellazzini et al. 2017; Leisman et al. 2017; Román & Trujillo 2017; Greco et al. 2018). These studies revealed that UDGs are common in galaxy clusters, galaxy groups, and as field galaxies.

The Coma cluster host a large UDG population. Initial observations with the Dragonfly Telephoto Array discovered 47 UDGs (van Dokkum et al. 2015a), but in a follow-up study, carried out by surveying deep Suprime-Cam/Subaru R-band images of the Subaru data archive, Yagi et al. (2016) detected a population of 854 UDG candidates in the Coma cluster. Given the massive nature and the relative proximity of this cluster, it has been well studied and has rich multiwavelength observations. Specifically, it was the target of multiple Chandra campaigns, observations that explored the galaxy cluster out to $\sim 1^\circ$ radius. These observations offer a unique opportunity to study UDGs residing in the Coma cluster. In this study, we employ Chandra observations of Coma cluster UDGs to address two critical science goals: (1) we probe the formation scenarios of UDGs and (2) we measure their AGN occupation fraction, i.e., the fraction of UDGs that are occupied by an active galactic nucleus.

The curious properties of UDGs can be explained by different formation scenarios. UDGs may be the descendants of massive galaxies that lost their gas content at high redshift (van Dokkum et al. 2015a, 2016). Alternatively, UDGs could be genuine dwarf galaxies (Chamba et al. 2020), whose large spatial extent is due to feedback-driven gas outflows (e.g., Amorisco & Loeb 2016; Beasley & Trujillo 2016). In this scenario, most physical characteristics of UDGs, such as their dark matter halo mass, are similar to those of dwarf galaxies.

Measuring the dark matter halo mass of UDGs offers a robust method to distinguish between potential formation scenarios. If UDGs originate from massive galaxies, they will reside in massive dark matter halos with a virial mass of $M_{\text{vir}} \gtrsim 10^{14} M_\odot$. If, however, UDGs are puffed-up dwarf galaxies, they are expected to live in low-mass dark matter halos ($M_{\text{vir}} \lesssim 3 \times 10^{10} M_\odot$). X-ray observations provide a powerful tool to measure the total gravitating mass of galaxies. Indeed, empirical correlations revealed that the luminosity of the gaseous X-ray halo around galaxies is proportional to the galaxy’s total gravitating mass (Kim & Fabbiano 2013; Babek et al. 2018). Additionally, comprehensive X-ray studies demonstrated that low-mass galaxies, such as dwarf galaxies,
cannot retain a significant amount of X-ray-emitting gas due to their shallow potential well (David et al. 2006). By utilizing the relation between X-ray luminosity and total gravitating mass, we constrained the formation scenarios of isolated UDGs (Kovács et al. 2019). Specifically, we analyzed XMM-Newton X-ray observations to probe the X-ray characteristics of a sample of isolated UDG candidates identified in the Subaru data. We did not detect statistically significant X-ray emission from the individual galaxies or from the stacked set of galaxies. The absence of the detection demonstrates the lack of an X-ray halo, thereby suggesting that most isolated UDGs are puffed-up dwarf galaxies.

To follow-up on our previous study, we extend our analysis to UDGs residing in the Coma cluster (Yagi et al. 2016). We carry out a similar analysis to that presented in Kovács et al. (2019). Specifically, we study the gaseous X-ray halo of Coma cluster UDGs to constrain whether their luminosity is consistent with a high-mass or a low-mass dark matter halo. As a complementary approach, we also probe the dark matter halo mass of UDGs through their globular cluster (GC) population. Several UDGs were demonstrated to host a large number of GCs (van Dokkum et al. 2017), suggesting that these UDGs reside in massive dark matter halos (Burkert & Forbes 2020). GCs are known to effectively form low-mass X-ray binaries (LMXBs) through dynamical processes (Voss & Gilfanov 2007). These LMXBs are copious sources of X-ray emission. Hence, by probing the X-ray luminosity associated with GC-LMXBs, we can probe whether the bulk of UDGs hosts a large GC population, as would be expected if they reside in a massive dark matter halo.

The exquisite Chandra X-ray observations of the Coma cluster provide the opportunity to probe whether UDGs host AGNs. Therefore, for the first time, we constrain the AGN occupation fraction of UDGs. X-ray observations offer a powerful method to search for AGNs because they are sensitive to weakly accreting black holes (BHs). In the past decade, several studies explored the AGN occupation fraction of dwarf galaxies (e.g., Reines et al. 2013; Miller et al. 2015). Both X-ray studies and optical line diagnostics investigations revealed that a small fraction of dwarf galaxies host AGNs, whose mass is in the range $10^5 - 10^7 M_\odot$. Most previous studies focused on dwarf galaxies, and the population of UDGs was not considered. Given that the mass of BHs is interconnected with the stellar mass and dark matter halo mass of the host galaxy (e.g., Kormendy & Ho 2013; Bogdán & Goulding 2015), it is interesting to probe whether the AGN occupation fraction of UDGs is similar to that of dwarf or more massive galaxies.

We assumed $D = 103$ Mpc as the distance of Coma cluster. At this distance $1''$ corresponds to 0.476 kpc. The Galactic absorption toward the Coma cluster is $9.3 \times 10^{19}$ cm$^{-2}$ (HI4PI Collaboration et al. 2016). In this paper, we used standard $\Lambda$-CDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$. The errors quoted in the paper are 1$\sigma$ uncertainties unless otherwise noted.

This paper is structured as follows. Section 2 describes the sample of UDGs detected in the Subaru survey. In Section 3, we introduce the analyzed data and discuss their reduction. In Section 4, we place constraints on the formation scenarios of UDGs. Our result for the AGN occupation fraction is presented in Section 5. We discuss the results in Section 6 and summarize in Section 7.

### 2. UDGs in the Coma Cluster

To study a large and homogeneous sample of UDGs, we rely on UDGs residing in the Coma cluster. Coma was the first galaxy cluster in which the Dragonfly Telephoto Array discovered a significant population of UDGs (van Dokkum et al. 2015a). The initial Dragonfly survey was followed by a deeper study (van Dokkum et al. 2015b) and the Subaru Suprime-Cam survey, which revealed 854 UDG candidates in the Coma cluster (Yagi et al. 2016). We note that the bulk of these galaxies should be considered as UDG candidates, because spectroscopic distance measurements are only available for a fraction of them. Due to the faint nature of UDGs and the large angular extent of the Coma cluster, it is demanding to measure the radial velocities of a large set of UDGs. However, using optical spectroscopic data from 10 m class telescopes, the radial velocities of small samples of UDG candidates were measured. These studies confirmed that most UDG candidates are members of the Coma cluster, and only a few of them reside behind it (van Dokkum et al. 2016, 2017; Kadowaki et al. 2017; Alabi et al. 2018; Gu et al. 2018). While these measurements are encouraging, some of the candidate UDGs without accurate radial velocity measurements may not reside in the Coma cluster. This, in turn, could imply that their true effective radius is less than 1.5 kpc if they are projected to the Coma cluster and the distance $D$ of the galaxies is significantly less than 103 Mpc.

In this work, we study the publicly available UDG candidates identified by Yagi et al. (2016). These galaxies are distributed in a $1^\circ$ region around the center of the Coma cluster. By utilizing the archival Chandra observations in the footprint of the Coma cluster and excising the central $4^\prime$ region (Section 3), we find that 404 UDG candidates have Chandra observations.

The Subaru survey provides magnitudes in $B$ and $R$ bands. To derive the stellar mass of the galaxy sample, we compute the $R$-band mass-to-light ratios using the $B - R$ color indices and rely on the results of Bell et al. (2003). Most UDGs have stellar masses in the range $10^6 - 10^7 M_\odot$. The stellar mass distribution of the galaxies is presented in the left panel of Figure 1. Based on the $B - R$ color indices we establish that most UDGs in our sample are red galaxies (right panel of Figure 1) and have little to no star formation. This conclusion is in good agreement with that obtained for the full sample (Yagi et al. 2016).

### 3. Data Analysis

In this work, we focus on Chandra ACIS imaging observations of the Coma cluster. To identify suitable data, we searched for publicly available observations within a $1^\circ$ (or 1.71 Mpc) radius of the cluster center. We identified 59 observations with a total exposure time of 1954.4 ks. These observations include 17 ACIS-S and 42 ACIS-I observations. The analyzed set of Chandra observations along with their exposure times are listed in Table 1.

We prepared and analyzed the data using standard CIAO tools (version 4.11) and used the most recent Calibration Database (CalDB version 4.8.4.1). To apply the latest calibration files on the data, we reprocessed all observations.
of our sample is consistent with the full list of UDGs. The red vertical line denotes the boundary between quiescent and star-forming color regimes.

Figure 1. Left: the stellar mass \( (M_\ast) \) distribution of the analyzed UDGs calculated using the \( R \)-band magnitudes and \( B - R \) color indices from Yagi et al. (2016). For the computation, we assume that the galaxies are at the distance of the Coma cluster. Right: the \( B - R \) color index histogram of the analyzed UDGs. The distribution of our sample is consistent with the full list of UDGs (Yagi et al. 2016), with UDGs being mainly on the red sequence. This suggests the quiescent nature of the majority of the UDGs. The red vertical line denotes the boundary between quiescent and star-forming color regimes (Koda et al. 2015).

using the chandra_repro tool. Given that the main focus of the paper is to identify luminous X-ray sources, we did not filter flare-contaminated time intervals, because the longer exposure and the resulting higher sensitivity outweigh the effect of a potentially higher background level.

From the event lists, we constructed images in the 0.5–1.2 keV (soft) and 0.5–7 keV (broad) bands to study the emission from hot gas and LMXBs, respectively. Given the characteristic X-ray spectrum of the gaseous emission and the population of LMXBs, these energy ranges are ideal to maximize the signal-to-noise ratios. We generated exposure maps for each observation assuming a different spectrum for each band, which corrects for vignetting effects and allows us to convert the counts to flux. For the soft-band images, we assume an optically thin thermal plasma emission model (APEC model in XSpec) with a temperature of 0.2 keV and a metallicity of \( Z = 0.2 Z_\odot \), which typically describes the gaseous emission of low-mass elliptical and spiral galaxies (e.g., Bogdán & Gilfanov 2011; Goulding et al. 2016). Although individual galaxies exhibit some variations in their best-fit gas temperature and metallicity, these potential variations do not affect our results, especially when investigating large samples of galaxies. For the broad-band images, we assume a power-law model with a slope of \( \Gamma = 1.7 \). This spectrum is typical for AGNs and LMXBs (e.g., Reeves & Turner 2000; Irwin et al. 2003; Piconcelli et al. 2005). We co-added the individual images and exposure maps to generate a large mosaic of the Coma cluster. The exposure-corrected broad-band image is presented in Figure 2.

To identify point sources we ran the CIAO WAVDETECT tool on the merged images. To this end, we also generated maps of the point-spread function for each observation with the MKPSFMAP tool. Similarly to the images, we also merged the individual maps of point-spread function. We searched for point sources on multiple scales by running WAVDETECT with the wavelet scales of the square-root-of-two series from \( \sqrt{2} \) to 32. The point-source lists contain 211 and 395 sources in the soft and broad bands, respectively. To derive the flux of the detected sources, we used the power-law spectrum with a slope of \( \Gamma = 1.7 \) and the line-of-sight column density of the Coma cluster. To account for the background emission, we used local regions around each point source. The applied background regions were elliptic annuli, whose inner and outer radii were two and three times the radius of the source region. This approach allows us to simultaneously account for both the instrumental and sky background components. This latter background component includes the unresolved emission from cosmic X-ray background sources, the local foreground emission, and most notably the large-scale emission from the Coma cluster, which exhibits significant spatial variations.

The central regions of the Coma cluster are dominated by an extremely bright core (e.g., Briel et al. 1992; Churazov et al. 2012). In these regions, the X-ray surface brightness of the intracluster medium largely exceeds the emission level expected from various X-ray-emitting components of UDGs. Therefore, we excluded the central 4\prime of the Coma cluster. This region approximately represents the cluster core with a flat surface brightness profile. Beyond this region the surface brightness of the intracluster medium rapidly drops and it plays a less significant role. We note that this region includes only seven UDGs, hence excluding the inner 4\prime does not affect our analysis in any significant way.

4. Constraining the Formation Scenarios of UDGs

In this section we probe whether the observed X-ray luminosities of Coma cluster UDGs are consistent with a scenario in which UDGs reside in Milky Way-type dark matter halos. If they reside in massive dark matter halos, UDGs should host a substantial amount of hot ionized gas and a copious population of LMXBs associated with their GC population. The total predicted X-ray emission is the combination of these (and possibly other) components (e.g., Gilfanov 2004; Bogdán & Gilfanov 2008, 2011; Boroson et al. 2011). In this work, we employ a conservative approach and assume that the main contribution to the soft and broad bands originates from the hot gas and LMXBs, respectively.
4.1. X-Ray Emission from Hot Gaseous Halos

To test the formation scenarios of UDGs, we first probe their hot gas content. The two different evolutionary scenarios imply drastically different halo masses (Section 1). Since the X-ray gas content and hence the X-ray luminosity of galaxies is proportional to their total gravitating mass \( M_{\text{tot}} \approx 10^{12} M_\odot \), measuring the X-ray luminosity of UDGs directly constrains the dark matter halo mass. Here, we carry out a similar analysis to that of Kovács et al. (2019), where we explored the X-ray gas content of isolated UDGs.

If UDGs are the descendants of massive galaxies, they are expected to live in Milky Way-type dark matter halos with \( \approx 10^{12} M_\odot \). This picture is supported by observations of several UDGs, such as DFX1 or Dragonfly 44 in the Coma cluster, which suggest that these galaxies reside in dark matter halos with masses of \( M_{\text{vir}} = (5 \pm 3) \times 10^{11} M_\odot \) (van Dokkum et al. 2016, 2017). To estimate the expected gaseous X-ray luminosity of a UDG with a massive dark matter halo, we assume a virial mass of \( M_{\text{vir}} = 8 \times 10^{11} M_\odot \), which corresponds to a total mass of \( M_{\text{tot}} = 1.8 \times 10^{12} M_\odot \) within \( r_{\text{eff}} \). Based on the \( L_{0.3-8 \text{ keV}} - M_{\odot} \) scaling relation, the expected X-ray luminosity of the gaseous halo is \( L_{0.3-8 \text{ keV}} \approx 1.8 \times 10^{39} \text{ erg s}^{-1} \). To convert this luminosity to the 0.5–1 keV band, we assumed a gas temperature of \( T = 0.2 \text{ keV} \) and a metallicity of \( Z = 0.2 Z_\odot \), which results in \( L_{0.5-1 \text{ keV}} \approx 1.1 \times 10^{38} \text{ erg s}^{-1} \). While the Chandra data of most individual galaxies are not sufficiently deep to detect this relatively low luminosity, a statistically significant signal may be obtained when the full sample of galaxies is stacked. Indeed, by stacking the X-ray photons associated with individual galaxies, we increase the signal-to-noise ratios, which allows us to probe the X-ray emission of the average UDG with better sensitivity.

We carry out the stacking analysis by utilizing the soft-band images and exposure maps, because we expect that the hot gas associated with the UDGs is relatively cool \( (kT \sim 0.2 \text{ keV}) \), i.e., most of the emission falls in the soft band. To stack the individual galaxies, we crop a 49\'\' \( \times \) 49\'\' region (or \( \sim 23.4 \text{ kpc} \times 23.4 \text{ kpc} \) at the distance of the Coma cluster) of the image and exposure map around each UDG. As the next step, we coadd the cropped images and exposure maps that were centered on the UDG coordinates as defined by the Subaru survey. The coadded soft-band image is presented in Figure 3.

To analyze the stacked images, we used a circular aperture with a 5\'\' radius. The background region was a circular annulus with radii of 10\'\' and 15\'\'. After accounting for the background emission, we did not detect a statistically significant signal from the stacked sample of UDGs. To place an upper limit on the X-ray luminosity of the hot gas, we took into account the source and background counts and the stacked exposure maps. We obtain a 2\( \sigma \) upper limit on the flux \( F_{0.5-1 \text{ keV}} < 7.2 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \), which—at the distance of Coma—corresponds to a luminosity upper limit of \( L_{0.5-1 \text{ keV}} < 9.1 \times 10^{37} \text{ erg s}^{-1} \). This value is \( \sim 12 \) times lower than that expected...
from a galaxy with a Milky Way-type dark matter halo (Figure 4). This suggests that most UDGs in the Coma cluster reside in dwarf-size dark matter halos. We note that this conclusion is in good agreement with our previous study for field UDGs.

4.2. X-Ray Emission from GC-LMXBs

A major surprise about UDGs was the detection of a large GC population. For example, Dragonfly 44 and DFX1 host 74 ± 18 and 62 ± 17 GCs, respectively (van Dokkum et al. 2017). This significant GC population exceeds the number of GCs typically found in dwarf galaxies, which host ≤10 GCs (Georgiev et al. 2008), and is comparable to that of massive galaxies, such as the Milky Way (Harris 1996). The large number of GCs around UDGs supports the formation scenario in which UDGs are descendants of massive galaxies and reside in massive dark matter halos.

X-ray studies of nearby galaxies established that the number of LMXBs per unit stellar mass is significantly higher in GCs than in the galactic field,5 which is attributed to different LMXB formation scenarios in the field and in GCs. Field LMXBs form through the primordial evolutionary path (Kalogera & Webbink 1998), while LMXBs residing in GCs form through dynamical interactions due to the dense stellar environment (Voss & Gilfanov 2006). Therefore, the distribution of field LMXBs follows the stellar mass (Gilfanov 2004), and GC-LMXBs are distributed following the $\rho_{\ast}^{-2/3}$ law (Fabian et al. 1975). Thanks to deep Chandra observations, the LMXB population of nearby galaxies has been studied to a great extent, and it was established that the X-ray luminosity

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5 In this context, galactic field LMXBs originate from the evolution of isolated binaries—sources that are typically located in the stellar body of the host galaxy.
functions of field and GC-LMXBs are different (e.g., Zhang et al. 2011; Peacock & Zepf 2016). Specifically, the luminosity function of GC-LMXBs is flatter at the faint end (<10^{−17} \text{ erg s}^{−1}) and the fraction of faint sources is factor of about four times less than that in the field population.

Given their low stellar mass and the lack of a dense stellar environment, we do not expect a substantial population of field LMXBs in UDGs. However, if UDGs reside in massive dark matter halos and host a substantial GC population, the LMXBs residing in GCs are expected to have significant X-ray emission. The X-ray luminosity of LMXBs is in the range $10^{33}−10^{39} \text{ erg s}^{−1}$, with only a small fraction of the GC-LMXBs exceeding $10^{38} \text{ erg s}^{−1}$ (Zhang et al. 2011). Therefore, given the currently available Chandra data, most LMXBs remain unresolved at the distance of the Coma cluster, and their emission contributes to the overall diffuse emission. When the emission from individual unresolved LMXBs is combined, we may detect significant X-ray luminosity. By confronting the predicted luminosity from GC-LMXBS with the observed luminosity around Coma cluster UDGs, we can constrain whether UDGs host a large number of GCs. This, in turn, allows us to probe whether UDGs reside in massive dark matter halos, thereby constraining their formation scenario.

Assuming that UDGs reside in a Milky Way-type dark matter halo with $M_{\text{vir}} \approx 8 \times 10^{11} M_{\odot}$ (Section 4.1), and applying the relation between the host galaxy mass and the number of GCs (Burkert & Forbes 2020), UDGs should host an average of 160 GCs. Based on the average GC-LMXB luminosity function, the predicted combined 0.5–7 keV band X-ray luminosity from GC-LMXBs is $\sim 9 \times 10^{39} \text{ erg s}^{−1}$.

To probe the population of Coma cluster UDGs as a whole, we co-add the X-ray data associated with the individual UDGs. The stacking procedure is identical to that outlined in Section 4.1, but the analysis is carried out for the broad band. We compute the luminosity associated with the stacked UDGs in a circular aperture with a radius of $S''$. To account for the background emission, we utilize a circular annulus with radii of $10''$ and $15''$. Given that the typical extent of GCs from the center of galaxies is $\sim 2.2 r_{\text{eff}}$ (van Dokkum et al. 2017), and the average effective radius of the analyzed UDGs ($r_{\text{eff}} = 2.5''$), we expect that most GCs will be confined within this aperture. We did not detect a statistically significant signal within the source aperture. In the absence of a detection, we compute a $2\sigma$ upper limit. Assuming a typical LMXB power-law spectrum, we obtained the flux upper limit of $F_{0.5−7 \text{ keV}} < 8.7 \times 10^{−17} \text{ erg s}^{−1} \text{ cm}^{−2}$, which corresponds to a luminosity upper limit of $L_{0.5−7 \text{ keV}} < 1.1 \times 10^{38} \text{ erg s}^{−1}$. We note that this is a conservative upper limit on the luminosity from GC-LMXBS since other sources may also contribute to the unresolved X-ray signal, with the most notable emission expected from the population of field LMXBs and high-mass X-ray binaries (HMXBs). However, as discussed in Kovács et al. (2019), the X-ray emission from these sources is of the order of $10^{35}−10^{36} \text{ erg s}^{−1}$, which is several orders of magnitude lower than the observed upper limit, implying that the emission from these sources does not affect our conclusions.

The upper limit on the luminosity is a factor of $\geq 80$ times lower than the luminosity predicted from a large population of GC-LMXBs. This suggests that most UDGs do not host a significant population of GCs. Taking the upper limit on the X-ray luminosity at the face value, we estimate that UDGs host a small GC population ($\sim 1.6$), which would imply a halo mass of $M_{\text{vir}} < 8.3 \times 10^{10} M_{\odot}$, consistent with dwarf galaxy halos (Read et al. 2017).

5. AGN Occupation Fraction of UDGs

5.1. Searching for AGNs in UDGs

To search for AGNs in UDGs, we cross-correlated the coordinates of the detected X-ray point sources in the Coma...
cluster with the position of the UDGs in both the soft and broad bands. When matching the X-ray sources with the center of galaxies, a search radius needs to be defined. The search radius depends on the positional accuracy of the Chandra point-source detection, which is determined by the number of source and background counts and the off-axis distance. In-depth studies demonstrate that the typical position offset between the center of Sloan Digital Sky Survey (SDSS) galaxies and X-ray sources is ~0\" ± 0\".4. Moreover, for >97\% of the sources the offset is <2\"5, even for those with a large off-axis distance (Kim et al. 2007; Trichas et al. 2012). Based on these figures, we conservatively use a search radius of 2\"5. After cross-correlating the X-ray source positions with the central coordinates of UDGs, we did not find any matches within 2\"5.

Because UDGs have relatively flat surface brightness profiles (e.g., van Dokkum et al. 2016), and simulations and observations suggest that a notable fraction of dwarf galaxies have BHs that are wandering within a few kiloparsecs of the galaxy center (Bellovary et al. 2019; Reines et al. 2020), we considered whether UDGs may host off-center BHs. Therefore, we increased the search radius to 5\". Given the typical effective radius (r_{\text{eff}} = 2\"5) of UDGs in our sample, this search radius broadly corresponds to 2r_{\text{eff}} at the distance of the Coma cluster.

Using the large search radius of 5\", we identified two galaxies, UDG 317 (r_{\text{eff}} = 2\"7) and UDG 412 (r_{\text{eff}} = 1\"8), which match with a detected X-ray source. The Chandra images of these two galaxies and the associated X-ray point sources are shown in Figure 5. We note that the relatively extended nature of the point sources is due to the ~4\" size of the weighted point-spread function at the location of both X-ray sources. The offset between the galaxy centroid and the X-ray source positions is 3\"0 for UDG 317 and 3\"2 for UDG 412. At the distance of the Coma cluster, these offsets correspond to ~1.4 kpc and ~1.5 kpc, respectively. We note that the detection of offset AGNs may not be unusual in dwarf galaxies. Indeed, cosmological simulations (Bellovary et al. 2019) of dwarf galaxies suggest that ~50\% of dwarfs may host their “central” BHs off-center, of which one-third lie >1 kpc off-center, mostly concentrated between 1 and 1.5 kpc.

### 5.2. The X-Ray Sources in UDG 317 and UDG 412

Assuming that the X-ray point sources are in the Coma cluster, the observed net count rates of (3.7 ± 0.3) × 10^{-3} s^{-1} and (5.5 ± 0.3) × 10^{-3} s^{-1} correspond to luminosities of L_{0.5–7 keV} = (1.3 ± 0.1) × 10^{39} erg s^{-1} and L_{0.5–7 keV} = (2.5 ± 0.1) × 10^{39} erg s^{-1} for UDG 317 and UDG 412, respectively. If these UDGs reside in the Coma cluster and the X-ray sources are within the galaxies, they are most likely off-center low-luminosity AGNs. Indeed, the luminosity of both X-ray sources exceeds 10^{39} erg s^{-1}, which is above the cutoff luminosity of LMXBs (Gilfanov 2004). While HMXBs or ultraluminous X-ray sources (ULXs) may reach luminosities in excess of 10^{39} erg s^{-1}, these types of sources are associated with active star formation (Grimm et al. 2003; King 2004; Swartz et al. 2009; Mineo et al. 2012). However, UDG 317 and UDG 412 have color indices of B – R = 0.91 and B – R = 0.92, which suggest that they are passive galaxies without significant star formation (Koda et al. 2015). Therefore, it is unlikely that any of these sources are HMXBs or ULXs in these galaxies. As a caveat, we note that the galaxies or associated X-ray sources could be projected onto the Coma cluster. For example, if the galaxies and their point sources are foreground galaxies that reside at D ≤ 65 Mpc, the luminosity of the off-nuclear X-ray sources remains below 10^{39} erg s^{-1}. This luminosity could be explained by LMXBs.

Due to the low number of net counts (<100) associated with the X-ray sources, it is not possible to construct their X-ray energy spectrum. Therefore, we computed simple hardness
ratios to infer the nature of these sources. Since we detect <10 net counts in the soft band, we rely on counts measured in the hard (2–7 keV) and medium (1.2–2 keV) bands. We define the hardness ratio as \( HR = (F_{\text{hard}} - F_{\text{medium}}) / (F_{\text{hard}} + F_{\text{medium}}), \) where \( F \) is the exposure-corrected number of counts in the given energy band. For the X-ray sources in UDG 317 and UDG 412, we obtained hardness ratios of \( HR = 0.23 \) and \( HR = 0.20 \), respectively. The typical spectrum of AGNs can be described with a power-law model with a slope of \( \Gamma = 1.5–2 \), which results in hardness ratios of \( HR_{\text{model}} = 0.04–0.23 \), where the lower value corresponds to the slope of \( \Gamma = 2 \). Thus, the observed hardness ratios are consistent with a power-law model with a slope of \( \Gamma \sim 1.5–1.7 \), suggesting that the X-ray sources in UDG 312 and UDG 412 could originate from AGNs.

UDG 317 and UDG 412 are covered by 24 and 11 Chandra pointings, which allows us to probe whether the X-ray sources associated with these galaxies originate from multiple observations. We find that both X-ray sources are present in multiple X-ray images, although they are not detected individually in each observation. Thus, these sources are not only detected in a single observational epoch due to their stochastic brightening, such as an AGN outburst. However, a detailed investigation of the temporal variations of the X-ray sources is not possible due to the low number of counts and the consequently large statistical uncertainties.

To further investigate the X-ray sources in UDG 317 and UDG 412, we inspect the Coma cluster images taken by the Subaru (Yagi et al. 2016); these images are presented in Figure 6. Interestingly, we identify an optical source that is coincident with the X-ray source identified in UDG 317. The presence of the optical counterpart suggests that this source is an AGN. Indeed, if the X-ray source were an X-ray binary or a ULX, the donor star would be too faint to be detected at the distance of the Coma cluster. However, it is still possible that the AGN is not residing in the galaxy, but is a foreground or, more likely, a background object. To conclusively determine whether this source is truly an off-center AGN associated with UDG 317, the redshift of the UDG and the optical source should be measured. We do not detect an optical counterpart of the X-ray source in UDG 412. The non-detection of an optical source does not constrain the nature of the X-ray source. Specifically, it could be an AGN residing in the UDG, a high-redshift background AGN, or a luminous (foreground) X-ray binary. Thus, the true nature of these X-ray sources cannot be conclusively determined on the basis of the present data. Therefore, we plan to carry out an optical follow-up of UDG 317 and UDG 412 along with the associated sources, which will be subject to a future investigation.

5.3. AGN Occupation Fraction of the Coma Cluster UDGs

In this work, we identified luminous X-ray sources associated with UDG 317 and UDG 412. However, given the present data, the nature of these X-ray sources cannot be unequivocally constrained. In addition, we did not detect an X-ray source associated with the other 402 Coma Cluster UDGs in the Chandra footprint. Therefore, we place an upper limit on the AGN occupation fraction of UDGs. Based on the two potential off-center AGNs and the non-detections, the upper limit on the AGN occupation fraction of Coma cluster UDGs is \( f_{\text{occ}} < 0.5\% \).

5.4. Monte Carlo Simulations

Due to the large number of UDGs and the abundance of X-ray point sources in the Coma cluster, it is possible that some of the X-ray point sources associated with UDGs are due to
spatial coincidence. In this scenario, the X-ray sources are not AGNs in the galaxy but are background AGNs.

To assess the likelihood of random matches, we carried out Monte Carlo simulations. To this end, we randomly generated 404 coordinates within the Chandra footprint of the Coma cluster excluding the central 4′ region. Hence the number of random coordinates is the same as the number of UDGs used in our work. Then, using these random coordinates, we searched for matching X-ray sources within 5″ between the position of the detected X-ray sources and the random coordinates. To build a statistically meaningful sample, we repeated this experiment 10^3 times, each time for a different set of random coordinates. We recorded the number of matches for each simulation and present the results on a histogram in Figure 7. The number of random matches ranges between zero and seven with a mean of 1.11 and a median of 1.0, which corresponds to a mean chance occupation fraction of \( f_{\text{MC}}^{\text{occ}} = 0.27\% \). We find that \(~69\% of the simulations have zero or one random match and \(~20\% have two spatially coincident matches. Based on these numbers, it is likely that at least one, but possibly both, UDG–X-ray source pairs are the results of spatial coincidence.

6. Discussion

In this work, we probed the formation scenarios of UDGs by constraining their typical dark matter halo mass using multiple approaches. First, we probed the hot X-ray gas content of UDGs. We did not detect a luminous gaseous halo around individual galaxies or in the stacked sample, which demonstrates the absence of hot X-ray gas. This result resonates well with our earlier study of isolated UDGs (Kovács et al. 2019), and suggests that most UDGs reside in dwarf-sized dark matter halos in isolation and in rich environments.

If UDGs reside in massive dark matter halos, they should also host a significant GC population and hence a substantial number of GC-LMXBs. We constrained the X-ray emission originating from LMXBs residing in GCs. As we did not detect a statistically significant signal from GC-LMXBs, we placed an upper limit on the X-ray luminosity of LMXBs, which suggested that a typical UDG hosts \(~1.6\) GCs. We note that the upper limit on the number of GCs was derived based on the best-fit scaling relation between the total mass of galaxies and the number of GCs. Although this scaling relation is very tight, at low virial masses \( (M_{\text{vir}} \lesssim 10^{11}M_\odot) \) it exhibits somewhat larger scatter (Burkert & Forbes 2020). However, this scatter does not influence our conclusions in any significant way, since we stacked a large sample of UDGs—an approach that probes the average galaxy properties and guards against outliers. The low number of inferred GCs for UDGs is comparable with that obtained for dwarf galaxies and is about 1.5–2 orders of magnitude lower than that observed for massive galaxies. We also emphasize that the applied scaling relation between the total mass of galaxies and the number of GCs is empirical and is not based on a volume-limited galaxy sample; however, this work represents the largest published survey. We refer the reader to Burkert & Forbes (2020) for a discussion about details on potential biases. Overall, our results suggest that most UDGs live in dwarf-sized dark matter halos and are genuine dwarf galaxies. However, as a caveat, we mention that the formation efficiency of LMXBs depends on the metallicity of GCs (Kundu et al. 2003). Specifically, metal-rich red GCs are at least three times more efficient in forming LMXBs than metal-poor blue GCs. It is known that the stellar body of galaxies hosts red GCs, while the dark matter halo hosts blue GCs. Given that in UDGs we mostly expect blue GCs (Beasley & Trujillo 2016; van Dokkum et al. 2017), which are associated with the dark matter halo, we may expect a significantly lower LMXB formation efficiency. However, even if the formation efficiency is a factor of three lower, the difference between the observed and predicted X-ray luminosities is still a factor of 10–30. Thus, it is unlikely that most UDGs host a significant GC population.

In summary, our analysis of the Coma cluster UDGs strengthens the formation scenario in which UDGs are the puffed-up version of dwarf galaxies. Based on the present analysis and the results presented in Kovács et al. (2019), we suggest that most UDGs are genuine dwarf galaxies and originate from similar evolutionary scenarios in both isolated and rich environments. However, it cannot be excluded that a small subset of UDGs, such as Dragonfly 44, reside in extended dark matter halos. Deep X-ray observations with present-day X-ray telescopes can provide an independent method to measure the dark matter halo mass of individual galaxies. In addition, future X-ray observatories with large collecting areas and high spatial resolution, such as the proposed Lynx observatory, will be excellent tools to understand UDGs. Such future studies will allow the study of larger samples of UDGs over greater distances and will also enable us to accurately distinguish the X-ray-emitting components within these systems.

In this work, we also placed an upper limit on the AGN occupation fraction of UDGs. It is interesting to compare these results with the AGN occupation fraction obtained for other galaxies. Based on SDSS observations, Reines et al. (2013) studied a sample of about 25,000 emission-line galaxies with \( z < 0.055 \) (or \( D < 250\ Mpc \)) with stellar masses of \( 10^{8.5}M_\odot \lesssim M_\ast \lesssim 10^{11.5}M_\odot \). While this sample represents the population of dwarf galaxies, these galaxies are more massive than the UDGs in our study. They identified 151 galaxies that potentially host an AGN, implying an AGN occupation fraction of \(~0.5\%). As a caveat, we note that the sample of Reines et al. (2013) consists of optically detected AGNs, and therefore they...
can only identify relatively luminous AGNs, with high accretion rates.

In the framework of the AGN Multiwavelength Survey of Early-type galaxies (AMUSE) survey, Miller et al. (2015) probed the AGN occupation fraction of about 200 optically selected early-type galaxies. The stellar mass of the galaxies was in the range $10^{7.6} M_\odot \lesssim M_* \lesssim 10^{12} M_\odot$ and they revealed that the AGN occupation fraction in galaxies increases with stellar mass. For their lowest mass bin, $10^{7.6} M_\odot \lesssim M_* \lesssim 10^{9.5} M_\odot$, they obtained an AGN occupation fraction of $f_{\text{occ}} \sim 5.6\%$. While this value is about an order of magnitude higher than that obtained in our study, galaxies studied in the AMUSE survey reside at a distance of 15–27 Mpc, which, in turn, allows the detection of fainter X-ray sources. Specifically, our typical source detection sensitivity is few times $10^{39} \text{erg s}^{-1}$, whereas the faintest X-ray sources in the AMUSE survey have luminosities of few times $10^{38} \text{erg s}^{-1}$. Therefore, the higher AGN occupation fraction obtained for dwarf galaxies may be—at least in part—due to the more sensitive nature of the AMUSE survey. The difference in the AGN occupation fraction is even more striking between UDGs and massive galaxies. Galaxies in the AMUSE survey with $M_* > 10^{10} M_\odot$ exhibit an AGN occupation fraction of $f_{\text{occ}} \gtrsim 70\%$, which is more than two orders of magnitude higher than that obtained for UDGs in the Coma cluster. Clearly, the higher source detection sensitivity in the Coma cluster cannot account for this difference. Thus, we conclude that the AGN occupation fraction of UDGs is similar to or even lower than that obtained for dwarf galaxies.

As we discussed in Section 5, we computed the upper limit on the AGN occupation fraction based on two X-ray point source–UDG pairs. However, in the absence of precise spectroscopic redshift measurements, the distances of the galaxies and the X-ray sources are not known. Therefore, it is feasible that the matches are due to projection effects as suggested by our Monte Carlo simulations. Therefore, the X-ray point sources may not be associated with the UDGs, but could be background AGNs at higher redshift. Finally, it is also possible that the UDGs and the X-ray sources are only projected to the Coma cluster but are actually in the foreground. In this scenario, the intrinsic X-ray luminosity of the sources may be significantly lower, and hence the sources could be X-ray binaries. To clarify these issues, we plan to carry out spectroscopic measurements, which will establish whether the UDGs reside in the Coma cluster and whether the X-ray source associated with UDG 317 is at the same distance as the galaxy itself. However, this analysis is beyond the scope of this paper and will be the subject of a future study.

7. Conclusions

We performed an X-ray analysis on 404 Coma cluster UDGs identified by the Subaru Suprime-Cam survey. We probed the formation scenario of UDGs using two methods: measuring the X-ray luminosity expected from hot gas and measuring that from GC-LMXBs. In addition, we constrained the AGN occupation fraction of UDGs. Our results can be summarized as follows.

1. We measured whether UDGs host a significant amount of hot X-ray-emitting gas, which would be expected if they reside in a massive dark matter halo. We carried out a stacking analysis in the energy range 0.5–1.2 keV but did not detect a statistically significant signal. We placed an upper limit of $L_{\text{hot}} < 9.1 \times 10^{37} \text{erg s}^{-1}$ on the luminosity of hot gas. This upper limit falls a factor of ~12 times below the luminosity expected from UDGs with massive dark matter halos.

2. We constrained whether UDGs host a significant population of GCs. To this end, we probed the X-ray emission originating from the unresolved population of LMXBs residing in GCs. We did not detect statistically significant X-ray emission from the stacked sample, and placed an upper limit of $L_{\text{broad}} < 1.1 \times 10^{38} \text{erg s}^{-1}$. This limit is at least 80 times lower than that predicted in a scenario where UDGs host a large GC population.

3. We searched for AGNs associated with the UDGs. We identified two X-ray source–UDG pairs within 5″, which may be off-center AGNs. Since we cannot confirm that the X-ray sources are associated with the UDGs, we place an upper limit of $f_{\text{occ}} < 0.5\%$ on the AGN occupation fraction of UDGs in the Coma cluster. This value is comparable to or even lower than that obtained for dwarf galaxies and falls short of the values observed for massive galaxies.

In summary, we conclude that the bulk of the UDG population are genuine dwarf galaxies and are not the descendants of massive galaxies. Combining the results presented in this work with our earlier study, we suggest that most UDGs undergo similar evolutionary scenarios in isolated and rich environments. However, as a caveat, we mention that it is feasible that a small subsample of UDGs may originate from a different formation channel, and may live in massive dark matter halos.

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