A Rich Satellite Population of the NGC 4437 Group and Implications of a Magnitude Gap for Galaxy Group Assembly History

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Abstract

Both observations and cosmological simulations have recently shown that there is a large scatter in the number of satellites of Milky Way (MW)–like galaxies. In this study, we investigate the relation between the satellite number and galaxy group assembly history using the r-band magnitude gap (Δm12) between the brightest and second-brightest galaxies as an indicator. From 20 deg2 of the Hyper Suprime-Cam Subaru Strategic Program Wide layer, we identify 17 dwarf satellite candidates around NGC 4437, a spiral galaxy with about one-fourth of the MW stellar mass. We estimate their distances using the surface brightness fluctuation method. Then we confirm five candidates as members of the NGC 4437 group, resulting in a total of seven group members. Combining the NGC 4437 group (with Δm12 = 2.5 mag) with other groups in the literature, we find a stratification of the satellite number by Δm12 for a given host stellar mass. The satellite number for the given host stellar mass decreases as Δm12 increases. The same trend is found in simulated galaxy groups in the TNG50 simulation of the IllustrisTNG project. We also find that the host galaxies in groups with a smaller Δm12 (like NGC 4437) have assembled their halo mass more recently than those in larger gap groups, and that their stellar-to-halo mass ratios increase as Δm12 increases. These results show that the large scatter in the satellite number is consistent with a large range of Δm12, indicating diverse group assembly histories.

Unified Astronomy Thesaurus concepts: Galaxy groups (597); Dwarf galaxies (416); Galaxy dark matter halos (1880); Distance indicators (394); Galaxy distances (590); Luminosity function (942)

1. Introduction

In the Lambda cold dark matter (ΛCDM) paradigm, galaxies form in the center of dark matter halos and evolve through hierarchical merging and accretion. Smaller halos that are accreted into larger halos and become gravitationally bound are called subhalos, which observationally correspond to the satellite galaxies. It is inferred that the more massive the dark matter halos are, the more abundant the satellite systems are.

This structure formation model has been tested by comparing observations with simulations. The well-known “missing satellites” problem (Klypin et al. 1999; Moore et al. 1999) is an example. With dark-matter-only cosmological simulations, Milky Way (MW)–like halos in the ΛCDM scenario are predicted to have far more satellites than observed around the MW, and it is considered as one of the “small-scale” challenges to ΛCDM (see Bullock & Boylan-Kolchin 2017, and references therein). This motivated numerous studies of individual satellite systems to find out whether the MW satellite population is representative among them, from the Local Volume (LV; D < 11 Mpc) host galaxies (e.g., M31; see McConnellie 2012; Martin et al. 2016; McCracken et al. 2018, for compiled data); M81, Chiboucas et al. 2009, 2011; Spencer et al. 2013; Müller et al. 2014; NGC 5128 (Centaurus A), Crnojević et al. 2014; Carlsten et al. 2017; Danielli et al. 2017; NGC 628, Davis et al. 2017; Crnojević et al. 2018; M101, Bennet et al. 2019; Müller et al. 2019; NGC 4258 (M106), Kim et al. 2019; M94, Smercina et al. 2019b; Bennet et al. 2021) to those at farther distances (NGC 3175, Kondapally et al. 2018; NGC 2950 and NGC 3245, Tanaka et al. 2018).

In more recent years, statistical studies of satellites around MW-like galaxies have been carried out (Geha et al. 2017; Carlsten et al. 2020a, 2020b; Habas et al. 2020; Carlsten et al. 2021; Mao et al. 2021; Roberts et al. 2021; Wang et al. 2021). Among them, Carlsten et al. (2021) presented a study of a large sample of dwarf satellite systems around 12 LV host galaxies within the projected distance to their host galaxy (Rh) of 150 kpc, to which surface brightness fluctuation (SBF) or tip of the red giant branch (TRGB) distances are measured. They found that the MW satellite luminosity function (LF) is typical among other MW-like LV hosts.

At farther distances beyond the LV, while it is more difficult to identify and confirm the membership of faint galaxies, clear advantages exist: there are a larger number of MW-like galaxies, and a smaller field of view is sufficient to survey the entire virial volume. Among others, the SAGA survey (Geha et al. 2017; Mao et al. 2021) presented a study of spectroscopically confirmed satellites with a homogeneous spatial and photometric completeness. The SAGA Stage II (Mao et al. 2021) presented 127 satellites within Rh = 300 kpc around 36 MW-like hosts at distance 25 Mpc < D < 40.75 Mpc. They suggested that the number of satellites (M_v < −12.3 mag) of the MW-like hosts is remarkably varied, from zero to nine. In their sample, the MW has a typical number of satellites.

Meanwhile, several theoretical studies found that baryonic cosmological simulations produce fewer observable satellites around MW-like hosts compared with previous simulation studies, which is consistent with observations (Fattahi et al. 2016; Sawala et al. 2016; Wetzel et al. 2016; Garrison-Kimmel et al. 2019; Font et al. 2021). Also, the diversity of satellite
number was shown by Engler et al. (2021), who studied satellite systems of 198 MW-like hosts found in the TNG50 simulation (Nelson et al. 2019a).

Thus, there is a growing consensus between observations and simulations that the number of satellites of the MW is typical among other observed and simulated systems. Besides, a large scatter in the number of satellites is recognized from both approaches.

One of the causes of the large scatter might be diverse galaxy assembly histories. In the hierarchical structure formation scenario, it is expected that an early-formed system would have already cannibalized its massive satellite galaxies, if they existed. Therefore, the early-formed system would likely have a small number of satellite galaxies, with the central galaxy dominating the brightness of the group. Indeed, Mao et al. (2021) noted that MW-mass galaxy groups with massive satellites in the SAGA survey have a larger number of satellites. In addition, Smercina et al. (2021) found a tight relationship between the mass of a galaxy’s most dominant merger and its number of satellites using stellar halo and satellite properties of eight nearby MW-like galaxies. As a metric for the galaxy’s most dominant merger, they used either the total accreted stellar mass or the mass of the most massive satellite.

In this view, a magnitude difference, or a magnitude gap (Δm12), between the brightest and second-brightest galaxies gives useful information about galaxy assembly history. A galaxy group with a large magnitude gap is likely to have assembled its mass at an early epoch. Indeed, fossil groups, which are massive groups observationally selected on the basis of r-band magnitude gap, Δm12 > 2 mag, and X-ray luminosity LX > 1042h50−2 erg s−1 (Jones et al. 2003), are considered to have assembled their mass earlier than nonfossil groups (D’Onghia et al. 2005) or have lacked recent infall of new massive satellites (Kundert et al. 2017; see Aguerri & Zarattini 2021 for a recent review of fossil groups). Note that Δm12 is largely varied among nearby galaxy groups. While the M81 group has a massive satellite, M82, and thus a small gap, Δm12 = 1.4 mag (calculated from de Vaucouleurs et al. 1991), the M94 group has only faint satellites in its virial volume and thus a very large gap, Δm12 = 9.9 mag (Smercina et al. 2018). However, only a few studies have examined the observational evidence of the anticorrelation between the magnitude gap and the number of satellites (Hearin et al. 2013; Wang et al. 2021). Hearin et al. (2013) found that Sloan Digital Sky Survey (SDSS) groups with small magnitude gaps (Δm12 < 0.2 mag) have a richer satellite system than large-gap groups (Δm12 > 1.5 mag) at a fixed velocity dispersion among group members as a mass proxy at about MW-mass range. They used a volume-limited galaxy group catalog complete down to the absolute r-band magnitude Mr = −19 mag identified in Data Release 7 of the SDSS. Therefore, their sample does not contain large-gap groups with the second-brightest galaxy fainter than Mr = −19 mag. These criteria would exclude most of the nearby galaxy groups with low mass. In addition, Wang et al. (2021) suggested that MW-mass galaxy groups with magnitude gaps smaller than 1 mag have richer satellite systems than those with larger magnitude gaps. However, most nearby galaxies have magnitude gaps larger than 1 mag. Therefore, to understand any relation between the magnitude gap and a large scatter in satellite number among nearby MW-like galaxies, more observations of nearby satellite systems with various magnitude gaps, as well as comparisons with simulations, are required.

Here we study satellite populations of the NGC 4437 group, which has a relatively small magnitude gap (Δm12 = 2.5 mag) among nearby galaxy groups but larger than the previously studied regime. Then we compare the NGC 4437 group with other nearby galaxy groups, as well as mock galaxy groups from cosmological simulations.

Object NGC 4437 (=NGC 4517) is an LV spiral galaxy (Mr = −20.71 mag, D = 9.28 ± 0.39 Mpc) with about one-fourth the stellar mass of the MW, forming a pair with NGC 4592, which is a Large Magellanic Cloud–mass dwarf spiral galaxy (Mr = −18.23 mag, D = 9.07 ± 0.27 Mpc; Kim et al. 2020). See Table 1 for the basic information for the two spiral galaxies. Although various surveys have detected several faint galaxies around NGC 4437 and NGC 4592, their relationship with these spiral galaxies was not defined except for CGCG 014-054, a late-type dwarf galaxy at a distance of 16.5 Mpc; Mei et al. 2007). See Table 1 for the basic information for the two spiral galaxies. Although various surveys have detected several faint galaxies around NGC 4437 and NGC 4592, their relationship with these spiral galaxies was not defined except for CGCG 014-054, a late-type dwarf galaxy at a distance of 16.5 Mpc; Mei et al. 2007). See Table 1 for the basic information for the two spiral galaxies. Although various surveys have detected several faint galaxies around NGC 4437 and NGC 4592, their relationship with these spiral galaxies was not defined except for CGCG 014-054, a late-type dwarf galaxy at a distance of 16.5 Mpc; Mei et al. 2007). See Table 1 for the basic information for the two spiral galaxies. Although various surveys have detected several faint galaxies around NGC 4437 and NGC 4592, their relationship with these spiral galaxies was not defined except for CGCG 014-054, a late-type dwarf galaxy at a distance of 16.5 Mpc; Mei et al. 2007).
This paper is structured as follows. In Section 2, we describe the HSC data and our detection of dwarf satellite candidates. In Section 3, we present SBF distances to the dwarf satellite candidates and discuss their membership in the NGC 4437 group. In Section 4, we describe the spatial distribution of the NGC 4437 group in comparison with simulated galaxy groups in the TN50 cosmological simulation. In Section 5, we discuss environmental properties and the correlations between the magnitude gap, number of member galaxies, and assembly history of low-mass galaxy groups. In the final section, we summarize our main results.

2. Data and Dwarf Satellite Galaxy Survey

We use the g- and i-band imaging data from the second public data release (Aihara et al. 2019) for the Wide layer of the HSC-SSP (Aihara et al. 2018) to search for dwarf satellite candidates around NGC 4437. The HSC is a wide-field optical imager mounted on the 8.2 m Subaru telescope. The survey consists of three layers, Wide, Deep, and UltraDeep, with a 5σ photometric depth of $r\sim26$, 27, and 28 mag, respectively.

The images from the HSC-SSP are fully reduced, sky subtracted, and coadded with the pipeline hscPipe designed for the LSST (Bosch et al. 2018; Ivezić et al. 2019). In hscPipe v6, astrometric and photometric calibrations were performed against the Pan-STARRS1 DR1 catalog (Aihara et al. 2019). Sky subtraction was carried out with two steps, and Aihara et al. (2019) showed that the technique preserves low surface brightness features better than previous versions of hscPipe. The pixel scale of the HSC images is 0.′′168 pixel$^{-1}$. The average seeing is 0′′58 in the i band and 0′′77 in the g band.

Object NGC 4437 is located in the WIDE12H field, one of the Wide layers of the survey. We first visually inspected the 5′ × 4′ (~0.8 Mpc × 0.6 Mpc at the distance of NGC 4437) area centered on NGC 4437 to search for extended objects. We restricted our search to galaxies larger than 10$''$ (450 pc at the distance of NGC 4437) by visual diameter extent because applying the SBF techniques to smaller low surface brightness galaxies would result in an insufficient signal-to-noise ratio (S/N). Also, we ruled out galaxies that show visually too small SBFs to be at a distance of about 9 Mpc.

Due to the proximity to the Virgo cluster in the sky (~12°3), some Virgo members may be included in this area. Among the objects of which a radial velocity can be found in the NASA Extragalactic Database (NED), we excluded galaxies that have a relative radial velocity with respect to NGC 4437 $|\Delta v_{\text{helio}}| > 400$ km s$^{-1}$. As a result, we selected Dw1, Dw3, Dw4, Dw6, Dw7, Dw12, Dw13, Dw14, Dw15, and Dw16 as our initial sample. The selected satellite candidates with velocity measurements are Dw1, Dw3, Dw4, Dw6, and Dw13 (Figure 1 and Table 2). If an object does not have a velocity measurement, we consider it as a satellite candidate.

Then we performed a semiautomated detection following Carlsten et al. (2020a) to detect low surface brightness galaxies and estimate the completeness of our search. In this process, we added Dw2, Dw5, Dw8, Dw9, Dw10, Dw11, and Dw17 to the sample.

As a result, we find 17 candidate galaxies that vary in size, surface brightness, and morphology. Their locations are shown in Figure 2. Table 2 lists basic information for our candidate galaxies. The coordinates and heliocentric velocities are obtained from NED. We derived the photometric properties of these galaxies from AUTO magnitudes obtained using SExtractor (Bertin & Arnouts 1996) to the HSC images. The faintest object in the r band is Dw8, with $m_r = 19.58 \pm 0.02$ mag (which would correspond to $M_r \sim -10.3$ mag assuming the distance of NGC 4437). The color range of our candidate galaxies is $0.2 \lesssim (g - r)_{0} \lesssim 0.9$.

To check if our survey is complete, we injected 20,000 artificial galaxies of various structural parameters ($-10.5 \leq M_i \leq -12$ mag and $23 \leq \mu_{e} \leq 26$ mag arcsec$^{-2}$) randomly into the survey field and performed semiautomated detection to find the recovery rate. We assume that our automated detection and visual search are complete for galaxies brighter than this range. Figure 3 shows a completeness map in r-band absolute magnitude and average surface brightness within the effective radius of our sample galaxies. For comparison, dwarf galaxies in the Local Group from McConnachie (2012) are displayed as gray open circles. The locations of our sample galaxies are overlapped with those of the Local Group dwarf galaxies. The recovery rates (completeness) are indicated by colors. In general, completeness decreases as the surface brightness decreases or the total magnitude becomes fainter. More than 70% of artificial galaxies with $\mu_{e} < 25$ mag arcsec$^{-2}$ and $M_r < -11$ mag are recovered.

For the following analysis, we adopt the AB magnitude in the HSC system, which is similar to the SDSS and CFHT systems (Kim & Lee 2021). We correct for foreground reddening on each galaxy based on the extinction maps by Schlafly & Finkbeiner (2011) and use a subpixel zero for corrected values.

3. Group Membership Confirmation Using SBF Distances

3.1. SBF Measurement

While SBF techniques have been widely used for measuring distances to bright early-type semiresolved galaxies (e.g., Tonry & Schneider 1988; Jerjen et al. 2000; Mei et al. 2005; Mieske et al. 2007; Cantillo et al. 2018; Blakeloe et al. 2021), recent studies have shown that SBF techniques are also useful for measuring distances to dwarf galaxies with various morphological types (Carlsten et al. 2019a, 2021; Kim & Lee 2021). Subtracting the contributions from contaminating sources is trickier in the dwarf regime, but with a statistical approach for background subtraction (Carlsten et al. 2019a) and using a g-band masking threshold (Kim & Lee 2021), one can derive reliable distances to dwarf galaxies.

In order to estimate the distances to the satellite candidate galaxies and confirm their group membership, we measure SBF magnitudes of the candidate galaxies following the methods described in Kim & Lee (2021). Here we briefly introduce the main steps of the SBF method and show examples of a dwarf spheroidal galaxy, Dw4, and a blue, asymmetric irregular galaxy, Dw16, in Figure 4.

In a nutshell, the SBF technique measures a point-spread function (PSF)–scale fluctuation (dashed lines in right panels of Figure 4) in the Fourier domain of the fluctuation image, (Galaxy $-$ Model)/$\sqrt{\text{Model}}$ (Figures 4(c) and (i)), where Galaxy denotes the observed galaxy image (Figures 4(a) and (g)) and Model corresponds to the smooth galaxy light component (Figures 4(b) and (h)). For making smooth galaxy models, we use GALFIT (Peng et al. 2002) for the galaxies that are well described by a single Sérsic model or median-filtered images for the galaxies with an asymmetric morphology or
star-forming regions, with the filter size set to 10 times the seeing size, following Kim & Lee (2021). Using such a filter size, the power spectra calculated using GALFIT and median-filtered image (e.g., black dots and gray crosses in Figure 4(e)) agree very well except for the largest scale ($k < 0.05$ pixel$^{-1}$), which is not used for the power spectrum fitting.

We choose an optimal area for SBF calculation of a galaxy to minimize measurement errors. We measured the SBF using various annular masks (blue ellipses in Figures 4(a) and (g)) and selected an area based on the galaxy’s surface brightness and size. The size, color, and mean surface brightness of the selected areas are shown in Table 3. For early-type or low surface brightness galaxies, the galaxy colors and fluctuation magnitudes do not depend significantly on the choice of area. In the case of Dw3, the inner and outer regions of the galaxy show different colors, indicating different stellar populations. Therefore, we divided the galaxy into an inner and an outer region and calculated their SBFs separately.

For subtracting fluctuations from background sources, namely foreground stars and background galaxies, we measure the fluctuations in multiple background fields as described in Carlsten et al. (2019a) and subtract the median power. Panels (d) and (j) show examples of background fluctuations, and panels (f) and (l) show the corresponding power spectra. In

Figure 1. Top: HSC $g$, $r$, and $i$ color images of the dwarf satellite candidate galaxies around NGC 4437. The white bars represent 10″ length. North is up, and east is to the left. Bottom: HSC $i$-band zoom-in images of the sample galaxies. The black bars also represent 10″ length.
### Table 2

A List of NGC 4437 Group Dwarf Satellite Candidates

| ID     | R.A.   | Decl. | $V_{\text{helio}}$ | $m_g$,0 | $m_r$,0 | $m_i$,0 | $(g - i)_0$ | $R_e$ | $\mu_{e,0}$ | $t_{\text{exp}}$ | Morphology |
|--------|--------|-------|-------------------|---------|---------|---------|-------------|------|-------------|--------------|------------|
| Dw1    | 187.266083 | 0.103806 | 1198 ± 13 | 15.15 ± 0.02 | 14.90 ± 0.02 | 14.55 ± 0.02 | 0.46 ± 0.02 | 27.9 | 23.5 | 1170/2430 | Tr          |
| Dw2    | 187.545510 | 0.873920 | 15.24 ± 0.02 | 14.78 ± 0.02 | 14.60 ± 0.02 | 0.46 ± 0.02 | 14.8 | 22.7 | 1170/1830 | Ir          |
| Dw3    | 187.765899 | 1.675697 | 1105 ± 5  | 17.41 ± 0.02 | 16.86 ± 0.02 | 16.60 ± 0.02 | 0.81 ± 0.02 | 7.0  | 22.7 | 1590/2070 | Sph         |
| Dw4    | 188.172714 | −0.612622 | 15.58 ± 0.02 | 17.93 ± 0.02 | 17.72 ± 0.02 | 0.88 ± 0.02 | 14.0 | 24.9 | 1590/3060 | Sph         |
| Dw5    | 188.283101 | −0.533046 | 750     | 15.84 ± 0.02 | 14.96 ± 0.02 | 0.52 ± 0.02 | 27.8 | 24.0 | 1590/2460 | Tr          |
| Dw6    | 188.289818 | −0.375221 | 18.34 ± 0.02 | 17.72 ± 0.02 | 17.49 ± 0.02 | 0.88 ± 0.02 | 6.8  | 23.1 | 1740/2260 | Sph         |
| Dw7    | 188.494603 | 0.386552 | 18.33 ± 0.02 | 17.89 ± 0.02 | 17.81 ± 0.02 | 0.54 ± 0.02 | 6.3  | 23.6 | 1020/1230 | Tr          |
| Dw8    | 188.580343 | −0.238891 | 20.06 ± 0.02 | 19.58 ± 0.02 | 19.42 ± 0.02 | 0.67 ± 0.02 | 4.7  | 24.4 | 1170/1830 | Sph         |
| Dw9    | 188.77153 | 0.793541 | 19.46 ± 0.02 | 19.10 ± 0.02 | 18.94 ± 0.02 | 0.54 ± 0.02 | 5.8  | 24.1 | 1890/2060 | Ir          |
| Dw10   | 189.049118 | 0.720478 | 18.88 ± 0.02 | 18.41 ± 0.02 | 18.21 ± 0.02 | 0.78 ± 0.02 | 6.8  | 24.1 | 1590/1460 | Sph         |
| Dw11   | 189.175590 | −0.430357 | 18.88 ± 0.02 | 18.44 ± 0.02 | 18.28 ± 0.02 | 0.21 ± 0.02 | 8.2  | 24.4 | 1020/1230 | Ir          |
| Dw12   | 189.328167 | 0.213417 | 863 ± 11  | 16.68 ± 0.02 | 16.12 ± 0.02 | 15.84 ± 0.02 | 0.88 ± 0.02 | 8.2  | 21.6 | 1890/1060 | Sph         |
| Dw13   | 189.472708 | −0.600737 | 19.84 ± 0.02 | 19.30 ± 0.02 | 19.22 ± 0.02 | 0.86 ± 0.02 | 5.2  | 24.2 | 1740/1660 | Sph         |
| Dw14   | 189.705284 | −0.597846 | 19.18 ± 0.02 | 18.83 ± 0.02 | 18.67 ± 0.02 | 0.62 ± 0.02 | 5.2  | 24.1 | 2460/1490 | Sph         |
| Dw15   | 189.760798 | −0.656024 | 16.82 ± 0.02 | 16.40 ± 0.02 | 16.27 ± 0.02 | 0.27 ± 0.02 | 17.0 | 24.1 | 2460/1090 | Ir          |
| Dw16   | 189.948333 | 0.041222 | 18.28 ± 0.02 | 17.71 ± 0.02 | 17.50 ± 0.02 | 0.79 ± 0.02 | 12.0 | 24.4 | 1170/1030 | Sph         |

Note. Galaxy references: Dw1, 2dFGRS N320Z113 (Metcalfe et al. 1989); Dw2, APMUKS(BJ) B122737.31+010900.4 (Maddox et al. 1990); Dw3, CGCG 014-054 (Zwicky et al. 1961); Dw4, MGC 34050 (Liske et al. 2003); Dw5, APMUKS(BJ) B123007.66−002012.9 (Maddox et al. 1990); Dw6, UKGC 285 (Karachentseva 1968); Dw7, APMUKS(BJ) B123035.83−000559.0 (Maddox et al. 1990); Dw10, SDSS J123506.51−004736.7 (SDSS Data Release 6); Dw11, SDSS J123611.78−004313.7 (SDSS Data Release 6); Dw12, APMUKS(BJ) B123408.34−000920.0 (Maddox et al. 1990); Dw13, MGC 5522 (Liske et al. 2003); Dw14, SDSS J123753.44−003602.6 (SDSS Data Release 6); Dw15, APMUKS(BJ) B123615.42−001923.4 (Maddox et al. 1990); Dw16, KDG 171 (Karachentseva 1968); Dw17, MGC 36065 (Liske et al. 2003). Here R.A., decl., and $V_{\text{helio}}$ are from NED recent values. Magnitudes are obtained from the AUTO magnitude of the SExtractor photometry. Magnitude errors include a calibration error of 0.017 mag (Aihara et al. 2019). Here $\mu_{e,0}$ indicates the average i-band surface brightness in half-light radius. Morphology indicates the dwarf galaxy morphological types classified by our visual inspection following Karachentsev et al. (2013; Sph for spheroidal galaxies, Ir for irregular galaxies, and Tr for transition types between spheroidals and irregulars).
addition, in order to mask young stellar populations that result in stochastic effects, we mask all of the sources brighter than a $g$-band masking threshold, $M_{g,\text{thres}}$. Kim & Lee (2021) showed that the rms of the SBF calibration is smallest in the case of $M_{g,\text{thres}} = -4.0$ mag among the five masking thresholds $M_{g,\text{thres}} = -3.5, -4.0, -4.5, -5.0, \text{and} -5.5$ mag.

However, without prior information on distance, it is impossible to know which apparent magnitude corresponds to $M_g = -4.0$ mag in absolute magnitude. Therefore, we try using five thresholds, $m_{g,\text{thres}} = 26.3, 25.8, 25.3, 24.8, \text{and} 24.3$ mag, corresponding to $M_{g,\text{thres}} = -3.5, -4.0, -4.5, -5.0, \text{and} -5.5$ mag at the distance of NGC 4437, $D = 9.28 \pm 0.39$ Mpc derived using the TRGB method (Kim et al. 2020). Note that the absolute masking thresholds change if a galaxy is located at a different distance. For example, at a distance of 11.68 Mpc (7.37 Mpc), the thresholds correspond to $-4.0, -4.5, -5.0, -5.5, \text{and} -6.0$ mag ($-3.0, -3.5, -4.0, -4.5, \text{and} -5.0$ mag).

Lastly, we use fluctuation–integrated color relations for dwarf galaxies in the HSC system in Kim & Lee (2021) to obtain SBF absolute magnitudes and derive distances to the satellite candidate galaxies. Kim & Lee (2021) derived fluctuation–integrated color relations for dwarf galaxies using the $gi$ HSC data for 12 nearby dwarf galaxies of various morphological types. They presented the $i$-band SBF calibrations for different masking thresholds (see their Table 3): $m_i = (-2.65 \pm 0.13) + (1.28 \pm 0.24) \times (g - i)$ in the case of $M_{g,\text{thres}} = -4.0$ mag, which leads to the smallest rms scatter of 0.16 mag.

### 3.2. Group Membership Confirmation

Figure 5 shows the SBF magnitudes of the dwarf galaxies using five different $g$-band masking thresholds. We plot our confirmed NGC 4437 group members as orange symbols and background galaxies as blue symbols. In this subsection, we describe how we decided the membership based on SBF distances.

In each panel, we plot the SBF–integrated color relations derived by Kim & Lee (2021), assuming the distance of 9.28 Mpc (to NGC 4437), as red lines. At the 9.28 Mpc distance, the masking thresholds correspond to $M_{g,\text{thres}} = -3.5, -4.0, -4.5, -5.0, \text{and} -5.5$ mag. With fainter $M_{g,\text{thres}}$, the slopes decrease and the $y$-intercepts increase. The relations assuming smaller and larger distances ($7.37, 11.68, \text{and} 14.71$ Mpc) and the corresponding absolute magnitudes are also shown. If the distance to a galaxy is similar to 9.28 Mpc, its SBF magnitudes are likely to overlap with the red shaded regions. This diagram can be used for roughly estimating distances and choosing which $m_{g,\text{thres}}$ to use.

The SBF magnitudes do not differ significantly within the error range according to the choice of a masking threshold for the galaxies in the color range $(g - i)_0 \geq 0.6$ mag, for example, Dw4, Dw5, Dw7, Dw11, Dw13, Dw14, and Dw17. The latter six galaxies have significantly fainter SBFs than Dw4. They are even fainter than the relations for $D = 14.71$ Mpc. Thus, they are likely Virgo members, not members of the NGC 4437 group.

In the bluer colors, the SBF magnitudes vary with the choice of a masking threshold. Therefore, deciding the membership of galaxies with bluer colors is more difficult. For instance, it seems that the SBF magnitudes of Dw1 and Dw6 are fainter than the galaxies with orange symbols for $m_{g,\text{thres}} = 26.3$ mag, but the differences decrease at brighter masking thresholds. However, in this case, deciding on a bright masking threshold is not recommended because the thresholds correspond to brighter absolute magnitudes if they are truly located behind the distance of NGC 4437; thus, young stellar populations might not have been properly masked. We decide that they are likely background objects, based on the fact that the SBF magnitudes of Dw1 agree with the relations for 11.68 Mpc, and those of Dw6 agree with 14.71 Mpc in the threshold range $m_{g,\text{thres}} \geq 25.3$ mag.
The SBF magnitudes of the Dw3 inner field and Dw12 seem to be slightly brighter than the other three galaxies with orange symbols. If they are located in front of NGC 4437, it will be better to refer to the cases for brighter masking thresholds than fainter thresholds. The SBF magnitudes of Dw12 overlap with the red shaded regions for the cases of $m_{g, \text{thres}} = 24.8$ and 24.3 mag, so we decide that it is likely a member of the NGC 4437 group. For Dw3, while the SBF magnitudes of the inner field show better agreement with the case of $D = 7.37$ Mpc than $D = 9.28$ Mpc, the outer field shows better agreement with the case of $D = 7.37$ Mpc than $D = 9.28$ Mpc.
agreement with \( D = 9.28 \) Mpc. Thus, membership confirmation based on SBF distances is more ambiguous. Fortunately, the velocity of Dw3 \( (v_h = 1105 \pm 5 \) km s\(^{-1}\)) is measured to be close to that of NGC 4437 \( (v_h = 1128 \pm 5 \) km s\(^{-1}\)); see \( v_{\text{helio}} \) in Tables 1 and 2), and we conclude that it is a likely member of the NGC 4437 group.

Figure 6 shows (a) distances, (b) SBF magnitudes, (c) distance measurement errors, and (d) total distance errors of the five likely members for five masking thresholds. Here \( M_{g,\text{thres}} \) is calculated assuming 9.28 Mpc distance. Except for Dw3 (outer region) and Dw15, distances do not vary systematically with the choice of masking thresholds. In the case of the outer region of Dw3, the systematic trend arises from varying apparent SBF magnitudes. On the other hand, the SBF magnitudes of Dw15 are constant, but the difference comes from calibrations. In panel (c), we display the measurement errors in megaparsecs. Measurement errors are the sum of power spectrum fitting errors and background subtraction errors. Large errors in Dw3 (outer region) and Dw16 are due to increased stochasticity in background subtraction in low surface brightness regions. In panel (d), we show the total errors, the sum of the measurement error, and the calibration error. Calibration errors dominate total errors. The calibration error is the smallest when using \( M_{g,\text{thres}} = -4.0 \) mag, which is also reflected in the total errors. We select \( M_{g,\text{thres}} = -4.0 \) mag for our final choice of distances. For Dw3, where the measured SBF distance is slightly different when using the inner and outer regions, we adopt the average value 8.24 ± 0.96 Mpc.

Table 3 lists distances calibrated using \( M_{g,\text{thres}} = 25.8 \) mag. For the five likely members, we assume that the masking threshold corresponds to \( M_{g,\text{thres}} = -4.0 \) mag and apply the calibration for such a threshold, \( M = (-2.65 \pm 0.13) + (1.28 \pm 0.24) \times (g - i) \)0 (rms = 0.16 mag). For the other likely background objects, we use calibrations for other thresholds depending on their SBF magnitudes. Here \( \sigma_D \) indicates the standard deviations of the SBF distances using multiple masking thresholds. Note that \( \sigma_D \) is generally negligible compared to calibration errors.

Figure 7 shows the distances and their error ranges of the dwarf galaxies. While the 2σ distance range of the five likely members (Dw3, Dw4, Dw12, Dw15, and Dw16) includes the distance of NGC 4437, 9.28 Mpc, that of the other galaxies does not. Adopting the criterion used by Carlsten et al. (2019b, 2021), which is confirming a dwarf as a background object whose 2σ distance lower bound is beyond the distance of the host, we consider these 12 galaxies as background galaxies. Note that all of the galaxies we newly added by the automated detection are confirmed as background galaxies, indicating that our initial visual inspection was conservative. Table 4 lists the confirmed members of the NGC 4437 group in the order of absolute magnitudes.

Among our likely members, Dw15 has the faintest r-band magnitude \( (M_r = -11.0 \) mag). We assume that our search is complete, at least down to \( M_r = -11 \) mag, among the galaxies with sufficient surface brightness to apply the SBF method.

### 4. Satellites beyond the Virial Radius

In the previous sections, we identified dwarf satellite candidates in about a \( 5^\circ \times 4^\circ \) area around NGC 4437 and found that seven galaxies (NGC 4437, NGC 4592, Dw3, Dw4, Dw12, Dw15, and Dw16) are members of the NGC 4437 group. In this section, we describe the spatial distribution of the galaxies in the NGC 4437 group and discuss it using simulated galaxy groups in TNG50.

#### 4.1. Spatial Distribution of the NGC 4437 Group

In Figure 2, we plot the spatial distribution of the likely members of the NGC 4437 group as red symbols. Black dashed circles indicate the virial radii of NGC 4437 and NGC 4592, 170 (1°) and 110 (0.7°) kpc. These values are derived by three steps: (1) converting \( K_s \)-band magnitudes to stellar masses assuming
$\frac{M_{g}}{L_{Ks}} = 0.6 \, M_{\odot}/L_{\odot}$; (2) assuming halo masses of $5.3 \times 10^{11}$ and $1.5 \times 10^{11} \, M_{\odot}$, respectively, based on the stellar-to-halo mass ratio (SHMR) from Behroozi et al. (2013; 0.024 and 0.007, respectively); and (3) deriving virial radii from the $R_{200}$ versus $M_{200}$ relation obtained from the TNG50 (see Section 5.2) group catalogs, log($M_{200}$) = 3 × log($R_{200}$) + 5.03. The parameters are listed in Table 1. Thus, our field of view covers an approximately $5R_{\text{vir}} \times 4R_{\text{vir}}$ area centered on NGC 4437. This spatial coverage is wider than most observational studies of nearby galaxy groups, which restrict the group members to those within the projected virial radius (e.g., Carlin et al. 2016; Smercina et al. 2018; Carlsten et al. 2021; Davis et al. 2021; Mao et al. 2021).

The distance between NGC 4437 and NGC 4592 is about twice the virial radius of NGC 4437. Object Dw4 is in the virial volume of NGC 4437; Dw12, Dw15, and Dw16 are located within the virial radius of NGC 4592; and Dw3 is relatively isolated, being outside of the virial radius of both NGC 4437 and NGC 4592. If we restrict the group members to those within the projected virial radius (dashed lines in Figure 2), we should regard NGC 4437 and NGC 4592 as primary galaxies of separate groups. However, given that their observed radial velocities are remarkably similar ($\Delta V_{\text{helio}} \sim 60 \, \text{km s}^{-1}$), it is likely that they are gravitationally bound. However, the velocity information is not conclusive because we do not know their tangential velocities. To decide whether or not to view the two galaxies as consisting of a single group, in the next subsection, we check the spatial extent and velocity distributions of galaxies in the TNG50 mock galaxy groups, especially if the galaxies located outside the virial radius of the host galaxies are truly gravitationally bound.

4.2. TNG50 Mock Galaxy Groups

We use group catalogs from the TNG50 simulation (Nelson et al. 2019a; Nelson et al. 2019b; Pillepich et al. 2019) of the IllustrisTNG project (Marinacci et al. 2018; Naiman et al. 2018; Nelson et al. 2018; Pillepich et al. 2018; Springel et al. 2018) to select mock galaxy groups. IllustrisTNG is a suite of large-scale cosmological galaxy formation simulations with
three different volumes and resolutions (TNG50, TNG100, and TNG300). We choose the smallest resolution, TNG50, which has the baryonic mass resolution $m_b = 8.5 \times 10^4 M_\odot$. The group catalog includes halos determined by a friends-of-friends (FoF) algorithm with a linking length $b = 0.2$ and substructures (subhalos) identified by the Subfind algorithm (Springel et al. 2001; Dolag et al. 2009).

4.2.1. Subhalo Selection

We only consider subhalos with SubhaloFlag = 1 and an instantaneous dark matter fraction larger than 10% to exclude noncosmological objects that are fragments or clumps produced through baryonic processes in already formed galaxies (Nelson et al. 2019a). We also restrict our analysis to luminous subhalos with stellar masses of at least $M_\ast \sim 2 R_{\text{eff}} = 5 \times 10^6 M_\odot$ measured within twice the stellar half-mass–radius following Engler et al. (2021) in order to avoid resolution effects. This stellar mass threshold roughly corresponds to $M_\ast \sim -11$ mag, similar to the completeness limit of our search of NGC 4437 group satellites. In the TNG50, 21,864 subhalos satisfy both criteria.

Black lines in Figure 8(a) show a stellar mass function of the selected subhalos.

4.2.2. Galaxy Group Selection

Next, we select galaxy groups based on two criteria. First, we limit our analysis to FoF groups with a total stellar mass larger than $10^9 M_\odot$. In the TNG50, 1928 FoF groups satisfy this mass limit. Red dotted lines in Figure 8 show the host galaxy stellar mass function of such groups. Here we define a host galaxy as the most massive subhalo among subhalos in an FoF group and

Table 4

| Name     | $M_\ast$ (mag)$^a$ | Distance (Mpc) | $V_{\text{helio}}$ (km s$^{-1}$) |
|----------|--------------------|----------------|-------------------------------|
| NGC 4437 | -20.71             | 9.28 ± 0.39    | 1128 ± 5                      |
| NGC 4592 | -18.23             | 9.07 ± 0.27    | 1069 ± 2                      |
| Dw3      | -15.05             | 8.24 ± 0.96    | 1105 ± 5                      |
| Dw16     | -13.44             | 9.80 ± 0.95    | ...                           |
| Dw4      | -12.98             | 9.69 ± 0.74    | 1192                           |
| Dw12     | -11.40             | 8.22 ± 0.66    | ...                           |
| Dw15     | -11.01             | 8.31 ± 0.63    | ...                           |

$^a$ For the dwarf galaxies, distances are assumed to be at the distance of NGC 4437, 9.28 Mpc.
satellite galaxies as the other subhalos. Second, we only consider galaxy groups that have at least one satellite galaxy brighter than $M_r = -11$ mag; that is, galaxy groups with at least one subhalo (other than the host subhalo itself) that satisfies the subhalo selection criteria. Red solid lines in Figure 8 display the host galaxy stellar mass function of the 661 groups that satisfy both criteria. Then we classify selected FoF groups according to host stellar mass: low-mass NGC 4437 group–like groups ($9.9 < \log [M_*/M_\odot] < 10.3; N = 203$), MW-like groups ($10.3 < \log [M_*/M_\odot] < 10.9; N = 237$), and massive groups ($10.9 < \log [M_*/M_\odot] < 11.5; N = 96$). These are indicated as vertical colored bars in Figure 8(b).

4.2.3. Spatial Extent of Simulated Galaxy Groups

Now we define two quantities to describe the spatial extent of simulated galaxy groups: $D_{\text{max}}$ and $D_{12}$. The $D_{\text{max}}$ of a galaxy group is the distance between the host galaxy and the farthest satellite galaxy ($M_r < -11$ mag). The $D_{12}$ of a galaxy group is the distance between the host galaxy and the second-brightest member galaxy. For the NGC 4437 group, $D_{12} = 0.29_{-0.30}^{+0.30}$ Mpc $\sim 1.7_{-0.25}^{+0.25} R_{200}$ (Kim et al. 2020). The $D_{\text{max}}$ is highly uncertain because of the wide distance error ranges in dwarf galaxies.

In Figure 9, we plot the histograms of two quantities in units of the virial radius $R_{200}$. The open histograms indicate all of the selected galaxy groups, and the filled histograms display NGC 4437 group–like galaxy groups. About half of the NGC 4437 group–like galaxy groups have $D_{\text{max}}$ larger than $R_{200}$, and about 10% of them are outside $2R_{200}$. About 30% of the NGC 4437 group–like galaxy groups have the second-brightest member galaxy outside $R_{200}$, and 10% are outside $2R_{200}$. This shows that although a majority of groups have $D_{\text{max}}$ and $D_{12}$ within $R_{200}$, a significant fraction of satellite galaxies lies outside $R_{200}$, like the case for NGC 4437 and NGC 4592.

To test if these large-distance satellite galaxies are truly bound to the host galaxies, we check their relative velocities. We find that a majority (75%) of the second-brightest member galaxies of galaxy groups with $D_{12} > R_{200}$ are infalling toward their host galaxies. The other 25% of them are receding from the host galaxy but have a velocity smaller than the escape velocity. Thus, it is likely that the second-brightest member galaxies outside $R_{200}$ will get closer to the primary galaxy and shortly become close satellites. Therefore, we conclude that galaxies grouped as an FoF halo in the TNG50 are bound, even though their separations are large.

To summarize, we find that a significant fraction of subhalos in an FoF group in the TNG50 simulation are located outside $R_{200}$ and that they are still bound to the host galaxy. Thus, we decide to view the NGC 4437 group, which has $D_{12} = 1.7 R_{200}$, as a single group.

5. Discussion

In this section, we discuss the properties of the satellites of the NGC 4437 group, in comparison with previous studies of low- and MW-mass galaxy groups and with cosmological hydrodynamic simulations.

5.1. Environmental Quenching of Satellites

The star formation properties of our satellite galaxies imply that environmental quenching has affected them. The two satellite galaxies (Dw4 and Dw15) that are located at the shortest projected distance to NGC 4437 and NGC 4592 are dwarf spheroidal galaxies with red colors ($g - i_0 = 0.81 \pm 0.02$ and $0.62 \pm 0.02$ mag, respectively), implying that they consist of old stellar populations. On the other hand, the satellites located farther from the pair of spiral galaxies (Dw3, Dw12, and Dw16) are late types with bluer colors ($g - i_0 < 0.5$ mag), and ultraviolet flux is detected from Galaxy...
Evolution Explorer images of them. This is consistent with earlier findings that the morphological type of the satellite galaxies around the MW, M31, M81, and M101 shows a strong correlation with projected distances from their host galaxies (Einasto et al. 1974) and with the color-projected distance relation that is well known for galaxy clusters (Dressler 1980) and the Local Group (van den Bergh 1994). Recent studies show that similar trends exist even for low-mass galaxy groups (Carlin et al. 2021; Davis et al. 2021). The satellite system of the NGC 4437 group supports the idea that environmental quenching plays a role even for low-mass galaxy groups, where lower ram pressure and tidal fields are expected.

5.2. Satellite LFs, Number of Member Galaxies, and the Magnitude Gap

There are seven galaxies ($M_r < -11$ mag) confirmed as members of the NGC 4437 group. In this subsection, we compare the spatially complete satellite population of the NGC 4437 group with the mock galaxy groups in the TNG50 cosmological simulation and other observed galaxy groups.

Figure 10 displays the observed cumulative LF of the members in the NGC 4437 group (thick black line) in comparison with the median LF of simulated NGC 4437 group–like galaxy groups (defined in Section 4.2). The median and ±1σ range of the LF of the simulated galaxy groups are shown as a red line with a red shaded region. The photometric limit of this study, $M_r = -11$ mag, is indicated by the gray shaded region. The NGC 4437 group has a relatively large satellite population compared to the simulated galaxy groups with a similar host stellar mass.

In addition, the median of the $M_r$ of the second-brightest galaxy in the simulated galaxy groups is about $M_r = -14.5$ mag. The second-brightest galaxy in the NGC 4437 group, NGC 4592, is relatively bright ($-18.2$ mag) among the NGC 4437 group–like simulated galaxy groups. This means that it has a relatively small magnitude gap ($\Delta m_{12} = 2.5$ mag) between the host galaxy (NGC 4437) and the brightest satellite galaxy (NGC 4592) compared to the simulated galaxy groups.

Previously studied observational evidence of the anticorrelation between $\Delta m_{12}$ and the number of satellites is based on the comparison between galaxy groups with a very small $\Delta m_{12} (< 0.2$ mag for Hearin et al. 2013 and $\Delta m_{12} < 1$ mag for Wang et al. 2021) and the rest. To check whether the anticorrelation extends to a larger gap regime for low-mass galaxy groups, we classify the simulated galaxy groups into five groups: $\Delta m_{12} < 5$ and $\Delta m_{12} < 7$.

Figure 11 displays the number of member galaxies of the group, $N_{\text{mem}}$, as a function of (a) host galaxy stellar mass and (b) host galaxy total mass from the TNG50 simulation. Here we consider the satellites brighter than $M_r = -12.3$ mag in order to match the magnitude limit of the SAGA survey (Mao et al. 2021), which will be described below. The five groups
The Astrophysical Journal, 929:36 (19pp), 2022 April 10

Kim et al.

The number of member galaxies ($N_{\text{mem}}$) brighter than $M_r = -12.3$ mag and the stellar mass of the host galaxies from the TNG50 simulation. Simulated galaxy groups are classified into five groups by their $\Delta m_{12}$, and their average and 1σ range of $N_{\text{mem}}$ are displayed as lines with shaded regions. The star indicates the NGC 4437 group. Diamonds and circles show the data from the SAGA survey (Mao et al. 2021) and the LV sample (McConnachie 2012; McConnachie et al. 2018; Carlsten et al. 2021; Carlin et al. 2021). Note the stratification of $N_{\text{mem}}$ by $\Delta m_{12}$ for a given host stellar mass.

Figure 11. (a) Relations between the number of member galaxies ($N_{\text{mem}}$) brighter than $M_r = -12.3$ mag and the stellar mass of the host galaxies from the TNG50 simulation. Simulated galaxy groups are classified into five groups by their $\Delta m_{12}$, and their average and 1σ range of $N_{\text{mem}}$ are displayed as lines with shaded regions. The star indicates the NGC 4437 group. Diamonds and circles show the data from the SAGA survey (Mao et al. 2021) and the LV sample (McConnachie 2012; McConnachie et al. 2018; Carlsten et al. 2021; Carlin et al. 2021). Note the stratification of $N_{\text{mem}}$ by $\Delta m_{12}$ for a given host stellar mass. (b) Relations between $N_{\text{mem}}$ ($M_r < -12.3$ mag) and the total mass of the host galaxies derived from the TNG50 simulation.

First, the positive correlation between $m_{12}$ and host stellar mass is seen in the simulated groups. The correlation is tighter against the total mass (including the dark matter halo mass) of the host galaxy. In addition, the number of satellites from the simulated groups shows a clear stratification in Figures 11(a) and (b): galaxy groups with a smaller $\Delta m_{12}$ have a larger $N_{\text{mem}}$. Note that the stratification of the same $\Delta m_{12}$ exists across a broad $\Delta m_{12}$ range.

We overplot the observed number of member galaxies and the host stellar mass in Figure 11(a) with colored symbols. Colors indicate the five groups of $\Delta m_{12}$. The circles and diamonds indicate the LV galaxy groups and SAGA survey sample, respectively. The LV sample, most of which is from the compilation by Carlsten et al. (2021), consists of 13 galaxy groups of which satellite membership is determined by measuring their distances using either the TRGB or SBF method: the MW (McConnachie 2012, for compiled data), M31 (McConnachie 2012; Martin et al. 2016; McConnachie et al. 2018, for compiled data), the Local Group (including the MW and M31 subgroups and quasi-isolated outlying members classified by McConnachie 2012), NGC 2403 (Carlin et al. 2021), NGC 4258 (Kim et al. 2011; Spencer et al. 2014; Carlsten et al. 2021), NGC 4631 (Tanaka et al. 2017; Carlsten et al. 2021), M51 (Carlsten et al. 2021), M101 (Bennet et al. 2017; Danielli et al. 2017; Carlsten et al. 2019b; Bennet et al. 2019), M94 (Smercina et al. 2018), NGC 1023 (Trentham & Tully 2009; Carlsten et al. 2021), M104 (Javanmardi et al. 2016; Carlsten et al. 2021), M81 (Chiboucas et al. 2009, 2013), and NGC 5128 (Cronjević et al. 2014; Müller et al. 2017; Cronjević et al. 2019; Müller et al. 2019). The other galaxy groups that are in the Carlsten et al. (2021) compilation but not this study are excluded because either the spatial coverage is too low (less than 20% of the projected virial area is covered) or the SBF S/N is too low to confirm satellites as faint as $M_r > -12.3$ mag. The SAGA survey sample (Mao et al. 2021) consists of galaxy groups with 36 MW-like host galaxies. The MW-like host galaxies are selected by their K-band magnitudes ($-24.6 < K < -23$ mag). The SAGA survey covered more than 80% of the projected $R_{20} = 300$ kpc area and confirmed satellite memberships from their redshifts. It is considered complete to satellites brighter than $M_r = -12.3$ mag. Note that while the spatial coverage of the LV sample significantly differs from galaxy to galaxy, and most of them cover less than the virial area, the SAGA survey sample has a relatively consistent spatial coverage.

Most of the references gave luminosities in bandpasses other than the r band. We converted the V-band magnitudes to r-band magnitudes using $M_r = M_V + 0.23$ (Engler et al. 2021). For SAGA hosts, we transformed $M_K$ magnitudes to $M_r$ magnitudes using the magnitude relations in TNG100 derived using 44 MW-like subhalos with the same $M_K$ range with SAGA selection criteria, $M_r = M_K + 2.48$ (rms $= 0.05$ mag). The MW-like subhalos are selected using the $g$, $r$, $i$, and $z$ magnitudes of the MW (Bland-Hawthorn & Gerhard 2016).

Although with a large scatter, the observed galaxy groups generally follow the simulated group lines. Also, the positive correlation between $N_{\text{mem}}$ and the host galaxy stellar mass and the anticorrelation between $N_{\text{mem}}$ and $\Delta m_{12}$ exists for observed galaxy group samples.

Figure 12 illustrates $N_{\text{mem}}$ as a function of $\Delta m_{12}$ for the same simulated and observed samples as in Figure 11. To account for host galaxy stellar mass, we sort our compiled sample into three...
mass groups according to their host stellar masses as defined in Section 4.2: NGC 4437–like ($9.9 < \log [M_*/M_\odot] < 10.3$; pink), MW-like ($10.3 < \log [M_*/M_\odot] < 10.9$; purple), and massive groups ($10.9 < \log [M_*/M_\odot] < 11.1$; blue). A majority of the galaxy groups belong to the MW-like groups.

Among the galaxy groups in the same mass range, the observational data for the groups clearly show a correlation between the number of satellites and $\Delta m_{12}$; the smaller the $\Delta m_{12}$, the richer the satellite system. The more massive groups have a larger $N_{\text{mem}}$ for a given $\Delta m_{12}$, although the sample numbers in the massive and low-mass groups are small. Again, the observed data generally follow the simulated group lines. The Spearman rank correlation coefficient between the $\Delta m_{12}$ and $N_{\text{mem}}$ of the SAGA sample (which is a dominant component of the MW-like groups) is $r_s = -0.58$ ($p$-value = $3.7 \times 10^{-4}$), which confirms that $\Delta m_{12}$ and $N_{\text{mem}}$ are anticorrelated.

We check this correlation in higher-resolution simulations, the FIRE project (Hopkins et al. 2014, 2018), a suite of high-resolution zoom-in simulations for MW-like galaxies. In their study of the relation between the merger history and satellite populations of eight nearby MW-like galaxies, Smercina et al. (2021) defined the stellar mass of the dominant merger ($M_{*,\text{Dom}}$, defined as the greater of either the total accreted stellar mass ($M_{*,\text{acc}}$) or the stellar mass of the most massive satellite ($M_{*,\text{Dom,Sat}}$)). They suggested that $M_{*,\text{Dom}}$ shows no clear correlation with the number of satellites ($N_{\text{sat}}$ for $M_V < -9$ mag) in the FIRE simulation data, while it shows a strong correlation in the observational data (see their Figure 3). Note that the FIRE data used in their study cover a much smaller mass range of $\log M_{*,\text{Dom}}/M_\odot = 9.0$–$10.3$ than the observational data ($\log M_{*,\text{Dom}}/M_\odot = 8.5$–$11$).

Using the information from the FIRE sample in Table 3 of Smercina et al. (2021), we investigate relations between merger mass indicators ($M_{*,\text{Dom,Sat}}$ and $M_{*,\text{acc}}$) and the number of satellites ($N_{\text{sat}}$) in a group. Figure 13(a) shows a positive correlation ($r_s = 0.55$, $p$-value = 0.06) between $M_{*,\text{Dom,Sat}}$ and $N_{\text{sat}}$. However, there is a weak anticorrelation ($r_s = -0.45$, $p$-value = 0.14) between $M_{*,\text{acc}}$ and $N_{\text{sat}}$ in Figure 13(b). As a consequence, $M_{*,\text{Dom}}$ shows no correlation with $N_{\text{sat}}$ ($r_s = -0.17$, $p$-value = 0.59).

If we use the stellar mass ratio between the host galaxy and the most massive satellite galaxy ($M_{*,\text{Dom,Sat}}/M_{*,\text{host}}$), which is equivalent to $\Delta m_{12}$ assuming a constant mass-to-light ratio, we find a stronger correlation between $M_{*,\text{Dom,Sat}}/M_{*,\text{host}}$ and $N_{\text{sat}}$ ($r_s = -0.67$, $p$-value = 0.02), as seen in Figure 13(c). Thus, it is shown that the number of satellites increases as the mass ratio between the host galaxy and the most massive satellite galaxy decreases (or as their magnitude gap $\Delta m_{12}$ increases). This result is consistent with those from observational and the TNG50 data in this study (as in Figure 11).

In summary, both observational and simulation data show that there is a strong correlation among the three parameters of the galaxy groups; the number of member galaxies is correlated with host galaxy stellar mass and $\Delta m_{12}$.

5.3. Magnitude Gap as an Indicator of Galaxy Assembly History

Since the magnitude gap is correlated with the number of member galaxies, as well as with host galaxy stellar mass, it is likely to also correlate with group assembly histories. If most of the group mass has assembled at an early epoch, and no bright galaxy accreted since then, the galaxy group might lack bright satellites at present. If a bright satellite existed in the group, it would have been already cannibalized by the host galaxy. Therefore, $\Delta m_{12}$ is likely to be related to the mass accretion history.

This view is supported by the previous studies of fossil groups, which are generally defined as massive systems ($M_{*,\text{host}} < -21.5$ mag by Raouf et al. 2014) with a large magnitude gap ($\Delta m_{12} > 2$ mag). The fossil groups are known to have earlier formation times and lack recent satellite accretion (D’Onghia et al. 2005; Kundert et al. 2017). However, the correlation between $\Delta m_{12}$ and assembly history for galaxy groups with lower mass than the fossil groups is not well established.

In this subsection, we investigate host galaxy assembly histories as a function of $\Delta m_{12}$ across a wide host mass range. In particular, we examine the cumulative total mass and stellar mass assembly histories, halo formation times, and SHMRs (the ratio of the total stellar mass to the total mass, including dark matter halos) of host galaxies in relation to $\Delta m_{12}$. For this purpose, we use the group catalogs from TNG50, as described in the previous subsection. From now on, we consider galaxy groups of which the second-brightest galaxy is brighter than $M_V = -11$ mag, which is the magnitude limit in our survey of the NGC 4437 group. As before, we divide our galaxy groups into three groups according to their host stellar mass—low-mass ($9.9 < \log [M_*/M_\odot] < 10.3$; $N = 306$), MW-like ($10.3 < \log [M_*/M_\odot] < 10.9$; $N = 241$), and massive ($10.9 < \log [M_*/M_\odot] < 11.5$; $N = 101$) groups—and examine their median properties. In each mass group, we divide simulated galaxy groups into five groups according to $\Delta m_{12}$.

The upper and lower panels of Figure 14 display the total mass and stellar mass assembly histories (mass fraction with respect to the current mass as a function of redshift) of the galaxy groups. The black lines indicate the median assembly...
history of all groups. Less massive groups (left and middle panels) assemble their total mass at an earlier epoch compared to more massive groups (right panel), on average. This tendency is the opposite for the stellar mass assembly history. Less massive groups assemble their stellar mass at a later epoch, since most host galaxies of low-mass groups show continuous star formation until the present day, while those of massive groups are quenched.

The distributions of $\Delta m_{12}$ are shown in the histograms of Figure 14. For the MW-like and massive groups, the number of groups decreases with increasing $\Delta m_{12}$. In contrast, many of the low-mass galaxies have a large $\Delta m_{12}$.

We plot the median assembly history of each group divided according to $\Delta m_{12}$ with different colors (bluer for smaller $\Delta m_{12}$). Host galaxies with large $\Delta m_{12}$ assemble their total mass earlier than those with small $\Delta m_{12}$ in all three mass groups. This suggests that $\Delta m_{12}$ is a useful parameter that distinguishes different total mass assembly histories. On the other hand, no such trend exists for stellar mass assembly histories, as shown in the lower panels.

Next, we compare the halo formation times of groups with different $\Delta m_{12}$. The halo formation time is useful for parameterizing galaxy assembly histories. Here we examine two parameters, $z_{50}$ and $z_{80}$, where $z_{50}$ ($z_{80}$) is a redshift at which the host galaxy assembled 50% (80%) of its mass.

The left panels of Figure 15 display relations between $\Delta m_{12}$ and $z_{50}$. We show three mass groups separately in the top, middle, and bottom panels. Colors indicate the number of satellite galaxies with $M_r < -11$ mag. There are positive correlations between $\Delta m_{12}$ and $z_{50}$ in all three mass groups, with $r_c \sim 0.4$. Host galaxies of the galaxy groups with a smaller $\Delta m_{12}$ have a larger number of satellites and have assembled their total mass recently. For instance, 80% of low-mass galaxy groups with $7 < \Delta m_{12} < 9$ have assembled half of the mass as early as $z > 1$, while only 40% of low-mass groups with $\Delta m_{12} < 3$ have assembled half of the mass at $z > 1$. From this, it is inferred that NGC 4437 with a small magnitude gap ($\Delta m_{12} = 2.5$ mag) is likely to have assembled its mass later than other host galaxies with a large magnitude gap.

The middle panels show the relations between $\Delta m_{12}$ and $z_{80}$. The correlations for $z_{80}$ are stronger ($r_c \geq 0.5$) compared to $z_{50}$. This is consistent with the findings from Kundert et al. (2017) that the assembly history of fossil and nonfossil groups differs more in recent accretion history and that $z_{80}$ is a more useful parameter than $z_{50}$ in distinguishing them.

The right panels represent the SHMRs of host galaxies as a function of $\Delta m_{12}$. In all three mass groups, positive correlations exist between the two parameters. The correlation is stronger for more massive groups. This is consistent with previous findings that the SHMRs of fossil groups are larger than those of nonfossil groups, based on both observations and simulations (Harrison et al. 2012; Kundert et al. 2017). For low-mass groups, SHMRs span a relatively narrow range, meaning that halo masses are not much varied given stellar mass. The correlations are weaker; thus, $\Delta m_{12}$ does not likely say much about SHMRs, not to the same degree as for higher masses.

To summarize, $\Delta m_{12}$ informs the halo formation times and SHMRs of host galaxies, even for low-mass groups, in the same manner that can be inferred from the studies of fossil groups: galaxy groups with a large $\Delta m_{12}$ tend to have a small number of satellites, have assembled at an early epoch, and have a large SHMR. A large diversity in the number of satellites of nearby galaxies partially originates from diverse assembly histories, and an easily observable parameter, $\Delta m_{12}$, can be used as an indicator for assembly times.

Note that the simulated galaxy groups we use to derive correlations in Figure 15 are spatially more complete than most observed samples. We investigate the relation between the survey coverage and the Spearman correlation coefficients in Figure 16. We derive Spearman correlation coefficients five times using different radius limits for defining a group, $R_{80} = 150, 200, 250, 300,$ and 500 kpc. The $\Delta m_{12}$ and $N_{mem}$ are determined within each radius limit. In the left panel, we show the correlation coefficients between $\Delta m_{12}$ and $N_{mem}$ ($r_c(\Delta m_{12}, N_{mem})$), and in the right panel, we show $\Delta m_{12}$ and $z_{80}$ ($r_c(\Delta m_{12}, z_{80})$). We plot the correlation coefficients for three different mass ranges with colored circles and the median virial radii as vertical dotted lines. The absolute values of the correlations generally increase as the radius limit increases for both panels. The correlations are not significant if the satellite galaxies are searched only in the virial radius. Thus, for $\Delta m_{12}$ to be useful for inferring galaxy assembly histories, it is recommended that satellite galaxies are searched in a wide area as large as $\sim 2R_{vir}$.
Object NGC 4437 is a low-mass edge-on spiral galaxy ($M_r = -20.7$ mag) paired with a dwarf spiral galaxy, NGC 4592 ($M_r = -18.3$ mag). We searched for dwarf galaxies in the $5^\circ \times 4^\circ$ area around NGC 4437 in the Wide layer of HSC-SSP (Figure 2) and found 17 satellite candidates (Figure 1 and Table 2). Our automated detection and visual search are approximately complete down to $M_r = -11$ mag and cover $5R_{vir} \times 4R_{vir}$. Then we applied SBF techniques to estimate the distances to the satellite candidates and confirm their membership. Our main results are summarized as follows.

1. **Group membership confirmation.** Based on the SBF distances, we confirm five dwarf galaxies (Dw3, Dw4, Dw12, Dw15, and Dw16) as members of the NGC 4437 group. We try measuring the SBF with five masking thresholds for eliminating contaminating sources, $m_{\text{g,thres}} = 26.3, 25.8, 25.3, 24.8,$ and 24.3 mag. From the fluctuation–color diagram, we select five galaxies as likely members and the other 12 as likely background galaxies.

2. **Environmental quenching for low-mass systems.** The two dwarf galaxies, Dw4 and Dw15, that are located at the shorter projected distance to NGC 4437 and NGC 4592 consist of old stellar populations, while the other three show star-forming regions. This is consistent with previous findings that environmental quenching plays an important role in low-mass galaxy groups.

3. **Satellite richness of the NGC 4437 group.** Although NGC 4437 is an order of magnitude fainter than the MW, it has a similar number of satellites to those of MW-like galaxy groups. It has a richer satellite system than simulated galaxy groups from TNG50, selected by host stellar masses $9.9 < \log M_*/M_\odot < 10.3$. However, it has a typical number of satellites when compared with galaxy groups of similar $\Delta m_{12}$, defined as an r-band magnitude difference between the brightest and second-brightest galaxies.

4. **Magnitude gap and the number of member galaxies.** We find a stratification of the number of member galaxies by $\Delta m_{12}$: the smaller the $\Delta m_{12}$, the larger the number of satellites. This trend is seen both in TNG50 (as well as...
FIRE) simulations and in the observed galaxy sample (Figure 11).

5. **Magnitude gap and the galaxy assembly history.** From simulated spatially complete galaxy groups in TNG50, we find that galaxy groups (for a host galaxy stellar mass range $9.9 < \log M_*/M_\odot < 11.5$) with smaller $\Delta m_{12}$ assemble their total mass at a later epoch (Figure 14). Thus, they have relatively later halo formation times, $z_{50}$ and $z_{80}$, with $z_{80}$ being more tightly correlated to $\Delta m_{12}$. While the SHMR is correlated significantly with $\Delta m_{12}$ for massive groups ($10.9 < \log M_*/M_\odot < 11.5$), the correlation gets weaker with decreasing host stellar mass (Figure 15). These findings imply that $\Delta m_{12}$ provides information about assembly histories even for low-mass groups, and the diverse assembly histories may account for a large scatter in the observed satellite number of nearby galaxy groups. In addition, the correlations increase as the radius limit for group definition increases, showing that satellite galaxies should be searched in a wide area to use $\Delta m_{12}$ as an indicator for galaxy assembly.
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Figure 16. Spearman correlation coefficients between $\Delta m_{12}$ and $N_{mem}$ (left) and $\Delta m_{12}$ and $\Delta z$ (right) as a function of radius limits for defining a group. Vertical lines indicate the average virial radius of each group of mass ranges. For all three mass ranges, the correlations increase as the radius limit increases.
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