Edge-on H I-bearing Ultra-diffuse Galaxy Candidates in the 40% ALFALFA Catalog

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Abstract

Ultra-diffuse galaxies are objects that have very extended morphology and faint central surface brightness. Most UDGs are discovered in galaxy clusters and groups, but some are also found in low-density environments. The diffuse morphology and faint surface brightness make them difficult to distinguish from the sky background. Several previous works have suggested that at least some UDGs are consistent with exponential surface brightness profiles. The surface brightness of exponential disks is enhanced in edge-on systems, so searching for edge-on systems may be an efficient way to select UDGs. In this paper, we focus on searching for edge-on H I-bearing ultra-diffuse sources (HUDS) from the 40% Arecibo Legacy Fast ALFA (ALFALFA) catalog, based on Sloan Digital Sky Survey g- and r-band images. After correcting the observed central surface brightness to a face-on perspective, we discover 11 edge-on HUDS candidates. All these newly discovered HUDS candidates are blue and H I-bearing, similar to other HUDS in 70% ALFALFA catalog, and different from UDGs in clusters.

Key words: galaxies: evolution – galaxies: formation – radio lines: galaxies

1. Introduction

Ultra-diffuse galaxies (hereafter UDGs) were first discovered in the Coma cluster by van Dokkum et al. (2015a, 2015b, hereafter V15a and V15b), and have very faint central surface brightness $\mu_{0, a} \geq 24$ mag arcsec$^{-2}$ and very large effective radius $r_e \geq 1.5$ kpc, even as large as that of the Milky Way. After that, more UDGs were discovered in galaxy clusters. Koda et al. (2015) found nearly 1000 UDGs in the Coma Cluster, Muñoz et al. (2015) and Mihos et al. (2015) identified UDGs in the Fornax Cluster, Yagi et al. (2016) located 854 Subaru-UDGs in the Coma Cluster, Román & Trujillo (2017a) identified 80 UDGs in the cluster A168, van der Burg et al. (2017) found $\sim$2500 UDGs in 8 nearby MEneaCS clusters, and Venhola et al. (2017) located 9 UDGs in the Fornax cluster.

In addition to the UDGs detected in high-density environments, there are also many UDGs which have been detected in lower-density environments, some group samples (e.g., Martínez-Delgado et al. 2016; Merritt et al. 2016; Román & Trujillo 2017b; Shi et al. 2017; Trujillo et al. 2017; Bennet et al. 2018; Spelkens & Karunakaran 2018), and a few field sources: H I-bearing ultra-diffuse sources (HUDS) found in the 70% Arecibo Legacy Fast ALFA (ALFALFA) catalog (hereafter $\alpha$-70) by Leisman et al. (2017, hereafter L17) and two extended dwarf irregular galaxies (Bellazzini et al. 2017), very similar to UDGs.

The origins of UDGs are still unclear. V15a suggest that the UDGs are “failed” $\sim L_{\ast}$ galaxies. Amorisco & Loeb (2016) and Lim et al. (2018) suggest that UDGs are dwarf galaxies. However, after considering the work of both van Dokkum et al. (2015a, 2015b) and Muñoz et al. (2015), and according to the study of Zaritsky (2017), UDGs may have multiple origins. They may be both “failed” $\sim L_{\ast}$ galaxies and dwarf galaxies.

UDGs may also have various formation mechanisms, such as being formed by collision (Baushev 2018) or being reproduced by tidal stripping of dwarf galaxies within clusters (Carleton et al. 2019). The formation mechanism of gas-rich UDGs, which have bluer colors, is feedback-driven expansion (Di Cintio et al. 2017; Chan et al. 2018; Papastergis et al. 2017). These blue UDGs can be detected by H I surveys, such as the ALFALFA extragalactic H I survey (Haynes et al. 2011, L17).

Compared with optically selected UDGs, H I-selected UDGs tend to be dominated by gas-rich UDGs, which have much bluer color and prefer to inhabit much lower-density environments. Though H I surveys are powerful tools for detecting field UDGs because they directly measure redshift, they are biased against gas-poor UDGs in the field. For example, Jones et al. (2018) use the Santa Cruz Semi-analytic model (Somerville et al. 2015) to predict the population of field UDGs. This model produces nearly 10 times more objects than they observe in the HUDS population.

Between the diffuse blue field sources and red UDGs, it seems that there may be an evolutionary connection. Some literature studies (e.g., Yozin & Bekki 2015; Amorisco & Loeb 2016; Di Cintio et al. 2017; Rong et al. 2017) suggest that progenitors of red UDGs are the high-spin tail of field dwarf galaxies or dwarf galaxies that are undergoing feedback-driven gas outflows. Carleton et al. (2019) applied a semi-analytic model to tidally stripped UDGs, and the results indicate that for dwarf galaxies which settle in cored halos, the tidal stripping mechanism can reproduce the observed properties of UDGs in clusters. Therefore, blue UDGs may play an important role in the origin of red UDGs.

To study the properties of UDGs in greater detail, spectral observation is necessary. However, the faint surface brightness makes spectral observation much more difficult. Many previous works have shown that most UDGs are well fit by a Sérsic model with $n \sim 1$ (e.g., V15a Koda et al. 2015) or $n < 1$ (e.g., Merritt et al. 2016; Yagi et al. 2016; Román & Trujillo 2017a; Venhola et al. 2017), while only a few UDGs are well
fit by $n > 1$, even $n \sim 4$ (e.g., Yagi et al. 2016; Lee et al. 2017; Müller et al. 2018). L17 suggests that the profile of HUDS is better fit by $n = 1$. This may indicate that these galaxies are exponential-profile galaxies. For these kinds of galaxies, their edge-on perspective enhances their surface brightness, making them easier to find and also enabling optical spectral observations. Also, their edge-on direction is suitable for measuring their maximum rotating velocities.

In this paper, we use Sloan Digital Sky Survey (SDSS) DR7 images matched with the 40% ALFALFA H I survey to find edge-on HUDS candidates. In Section 2, we introduce the data we used and the data reduction. In Section 3, we select the edge-on HUDS candidates after correcting the central surface brightness to face-on orientation/ In Section 4, we compare the properties of edge-on HUDS candidates with those of other UDG samples, and present the results of our candidates. In Section 5, we discuss the uncertainty, selection effect, and mechanisms of our HUDS candidates. Finally, a summary is given in Section 6.

2. Data and Data Reduction

2.1. Data

The ALFALFA extragalactic H I survey probes the population of local H I-rich sources over a cosmologially significant volume (Giovanelli et al. 2005; Haynes et al. 2018). It covers 7000 deg$^2$ of the sky at high Galactic latitude. A catalog based on 40% of the overall ALFALFA survey sky coverage was released in 2011 (hereafter referred to as α40) (Haynes et al. 2011). It consists of 15,855 objects and covers 2800 deg$^2$ of the sky: $0^\circ 7^2 30^m < R.A. < 16^h 30^m$, $+04^\circ < decl. < +16^\circ$, and $+24^\circ < decl. < +14^\circ$ (the “spring” range) and $22^h < R.A. < 03^h$, $+14^\circ < decl. < +16^\circ$, and $+24^\circ < decl. < +32^\circ$ (the “fall” range). From its catalog, we can obtain many useful properties of galaxies: H I masses, H I profiles, velocity widths ($W_{50}$), redshifts, and so on. The H I masses of detected objects are from $10^8 M_\odot$ to $10^{10.8} M_\odot$.

The SDSS (York et al. 2000) consists of five bands (ugriz), composed of imaging and spectroscopic surveys. It covers 11,663 deg$^2$ of the sky, and has a field that overlaps with ALFALFA. In α40 (Haynes et al. 2011) there are 12,468 objects that have been matched with their optical counterparts (OCs) in SDSS DR7 (Abazajian et al. 2009). To compare with previous works, we adopt the g- and r-band SDSS images for searching and studying edge-on HUDS. For identifying selected objects, we also have checked their optical morphology with the Dark Energy Camera Legacy Survey, which is much deeper than SDSS and can provide higher quality images.

2.2. Data Reduction

The surface brightnesses of UDGs are too faint (nearly three magnitudes fainter than that of dark sky background) to be detected. Accurate background estimation is very important for searching for UDGs, but the Photo Pipeline of SDSS DR7 is not good at searching for low-surface-brightness objects. It always overestimates the sky background, and underestimates the luminosities and effective radius of galaxies. The average of the underestimation is 0.16 mag, and the maximum is 0.8 mag (Lauer et al. 2007; Liu et al. 2008; Hyde & Bernardi 2009; He et al. 2013; Du et al. 2015).

To eliminate such deviation, we adopt a more adaptive measurement, which has been reported by Zheng et al. (1999), Wu et al. (2002), and Du et al. (2015), to estimate the sky background of SDSS fpC-images of 12,468 galaxies using optical-H I cross-matches from Haynes et al. (2011). First, we detect all the objects in a fpC-image by SExtractor (Bertin & Arnouts 1996) after smoothing the image by a Gaussian Function with an FWHM of 8 pixels. Then we mask these detected objects and derive a sky background image using both the line and column linear fitting method (Zheng et al. 1999; Wu et al. 2002; Du et al. 2015).

Next, we use SExtractor again to perform surface photometry for the target objects after subtracting the sky background from the fpC-image. We adopt the AUTO photometry using the Kron flexible elliptical aperture (Bertin & Arnouts 1996). The final magnitudes are calibrated by the following formula from the SDSS DR7 website:

$$\text{mag} = -2.5 \times \log \left( \frac{\text{counts}}{\text{exptimes}} \right) - (aa + kk \times \text{airmass})$$  \hspace{1cm} (1)

Here, “aa” is the zero-point of the fpC-image and “kk” is the atmosphere extinction coefficient. “aa,” “kk,” and “airmass” are all given from drField.fit files of SDSS DR7. “Counts” is measured from the AUTO aperture by SExtractor in ADU units, and “exptimes” is the exposure time of SDSS imaging, 53,907,456 s. Additionally, we correct the measured magnitude for Galactic extinction, which is calculated by the dust map of Schlegel et al. (1998).

3. The Selection of H I-bearing Ultra-diffuse Sources

3.1. GALFIT Fitting

Previous UDG studies (e.g., V15a Koda et al. 2015; Merritt et al. 2016; Yagi et al. 2016; Román & Trujillo 2017a; Venhola et al. 2017) showed that the surface brightness profiles of UDGs are best fit by the Sérsic model $n \sim 1$ or $n < 1$. And L17 suggests that $n = 1$ is best for HUDS. So we also use the $n = 1$ in this work. Using the exponential-profile model by GALFIT (Peng et al. 2010), we can obtain the minor-to-major axis ratio, $b/a$, of each object. In the GALFIT fitting, the PSF image directly achieved from the SDSS is convolved to the galaxy image to correct the PSF smearing.

Du et al. (2015) have selected LSBGs with the ratio of $b/a > 0.3$ from the α40 catalog in both the g band and r band. This set excludes the edge-on galaxies. On the contrary, we use all these remaining cases of Du et al. (2015), whose $b/a \leq 0.3$. Then we check the images of these galaxies, and reject obviously irregular and interacting galaxies. We also remove some galaxies that are contaminated with nearby bright objects. Finally, 1670 edge-on galaxies remain. These galaxies have symmetrical edge-on, disk-like shapes with no visible spiral structures or dust lanes passing through their centers.

Then, we mask bright stars around the galaxies in the image, and use GALFIT with the edge-on exponential disk model to achieve more specific central surface brightness values of these edge-on galaxies. This fitting is sensitive to initial values, such as central surface brightness $\mu_0$, scale length $r_s$, scale height

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5 http://classic.sdss.org/dr7/algorithms/fxcal.html

4 http://legacysurvey.org/decamls/
$\rho_s$, and positional angle PA. If these values are far from the best fit, the fitting will easily break down.

As we do not know the exact values of these parameters, we give a range of each parameter to fit, and select initial values randomly from the range. We take a test for checking the scatter of fitting results by giving different initial values: the $\mu_{0,\text{edge}}$ is a random number in a range of 10–25, the $r_s$ is in the range from 2 pixels to 1.5 times the disk scale length, which is the output of SExtractor in Section 2.2, the $h_s$ is from 1 pixel to half of the input initial value of $r_s$, and the PA is the output of SExtractor, which is transferred to GALFIT coordinates. We take 100 loops in the test, and there are 34 loops that get good fitting results (a good result means there are no star signs in the result like ‘“0.01”’). The standard deviations of these results are 0.000057, 0.001387, 0.000077 and 0.000461 for $\mu_{0,\text{edge}}$, $r_s$, $h_s$ and PA respectively. The output results are convergent. So, once the fitting gets a good result in a loop, we can treat it as the best fitting result we need and continue to fit other galaxies. We display the fitting images of one edge-on galaxy AGC 202262 in Figure 1 as an example.

3.2. Central Surface Brightness Dependence on Inclination

However, this central surface brightness is just an observational one, and cannot represent the face-on exponential profile of the system. In fact, both central surface brightnesses are different and have a relation. From van der Kruit & Searle (1981) and Giovanelli et al. (1995) the face-on disk model is

$$\tilde{\mu}(R) = \tilde{\mu}_{0,\text{face}} e^{-\frac{R}{r_s}},$$

with $\tilde{\mu}_{0,\text{face}} = 2h_s\rho_0$, while the edge-on disk mode is

$$\tilde{\mu}(R, h) = \tilde{\mu}_{0,\text{edge}} \left( \frac{R}{r_s} \right) K_1 \left( \frac{R}{r_s} \right) \text{sech}^2 \left( \frac{h}{h_s} \right),$$

with $\tilde{\mu}_{0,\text{edge}} = 2r_s\rho_0$. Here, $\tilde{\mu}$ is surface brightness in luminosity units, $R$ is the radial distance from the center of the galaxy, and $h$ is the vertical distance from the disk. $\tilde{\mu}_0$ is central surface brightness, $\rho_0$ is central luminosity density, $r_s$ and $h_s$ are scale length and scale height of galaxy respectively, and $K_1$ is the modified Bessel function. Therefore, there is a relationship between the central surface brightness of face-on and edge-on disk galaxies:

$$\mu_{0,\text{face}} = \tilde{\mu}_{0,\text{edge}} \times h_s/r_s,$$

and transforming to magnitude units, this becomes

$$\mu_{0,\text{face}} = \mu_{0,\text{edge}} - 2.5 \times \log(h_s/r_s).$$

This central surface brightness of an edge-on galaxy is brighter than that of a face-on galaxy, as scale length is larger than scale height.

Upon correcting the central surface brightness $\mu_{0,\text{face}}$ and cosmological dimming effects (Trachternach et al. 2006; Zhong et al. 2008; Du et al. 2015), we get the $\mu_{0,\text{face}}$ of these 1670 edge-on galaxies. Then, we select HUDS using the criteria adopted by V15a: $r_{e,\text{e}} \geq 1.5$ kpc and $\mu_{e,0,\text{face}} \geq 24$ mag arcsec$^{-2}$. The $r_e$ can be calculated by $r_e = 1.678 \times r_s$ for a disk-like model fitting. There are only 11 galaxies that satisfy the criteria. Their SDSS DR7 and deeper DECaLS images, along with their H$\alpha$-line spectra, which are achieved from the NASA Extragalactic Database, are shown in Figure 2 and their general parameters are listed in Table 1. The absolute magnitudes of these galaxies are all fainter than $-17$ mag, and the color $g - r$ are bluer than 0.4.

From Figure 2, the globally integrated 21 cm emission lines of most of these HUDS candidates, except for AGC 202262, present double-horned profiles, which are a typical characteristic of disk galaxies (Bosma 1978). Considering the symmetrical thin edge-on disk-like optical shapes, these characteristics of H$\alpha$ velocity spectra and optical images support the argument that most of these HUDS candidates are possible edge-on disk galaxies with rotating H$\alpha$ gas.

3.3. Dust Extinction

However, the existing dust in exponential-profile systems would reduce the flux of edge-on galaxies. So generally we could not transform the central surface brightness just by Equation (5) simplistically. However, it is difficult to know the exact extinction relation between face-on and edge-on galaxies because of the unknown complex extinction inside the galaxies.

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Figure 1. Edge-on disk model fitting to the galaxy AGC 202262. From left to right these images show the fpC-image after sky subtraction and bright star removal in the model image and the residual image.
For estimating the internal extinction of our edge-on HUDS candidates, we have selected edge-on galaxies (\(b/a < 0.2\)) and face-on galaxies (\(b/a > 0.8\)) from the cross-matches between the \(\alpha.40\) catalog and the MPA-JHU DR7 catalog. These galaxies are further selected to be fainter than \(-17\) mag and \(g-r < 0.4\), which are the same as our edge-on HUDS candidates. Then, we removed those objects with poor spectral quality (having SNR of \(H_\beta\) and \(H_\alpha\) less than 5). With these selection criteria, 8 edge-on galaxies and 15 face-on galaxies remain.

Then, we use the flux ratios of \(H_\alpha\) and \(H_\beta\), which are provided by the MPA-JHU DR7 catalog, to estimate the \(g\)-band internal extinction \(A_g\) of each galaxy using the widely used Balmer decrement method. We apply the relationship between \(H_\alpha/H_\beta\) and \(E(B-V)\) (Calzetti 2001), and then...
Table 1
Parameters of the Edge-on HUDS Candidates

| AGC Nr | R.A. (J2000) | Decl. (J2000) | $M_g$ (mag) | $g - r$ (mag) | $r_{g,e}$ (kpc) | $\mu_{g,0,\text{edge}}$ (mag arcsec$^{-2}$) | $\mu_{g,0,\text{face}}$ (mag arcsec$^{-2}$) | $cz$ (km s$^{-1}$) | Dist$^a$ (Mpc) | $W_{50}$ (km s$^{-1}$) | $lg(M_{50}/M_\odot)$ | $lg(M_*/M_\odot)$ | $M_{50}/M_*$ | $\epsilon$ $^f$ |
|--------|--------------|--------------|--------------|---------------|----------------|---------------------------------|--------------------------------|---------------|---------------|----------------|----------------|----------------|----------------|---------------|
| 102276  | 00:49:52     | +25:56:39    | $-16.51 \pm 0.07$ | $0.35 \pm 0.02$ | $4.05 \pm 0.14$ | $22.48 \pm 0.01$ | $24.01 \pm 0.02$ | $4984$ | $69.6 \pm 2.2$ | $149 \pm 4$ | $9.10 \pm 0.06$ | $8.35 \pm 0.05$ | $5.68 \pm 1.05$ | $0.91 \pm 0.01$ |
| 113816  | 01:18:47     | +24:27:14    | $-15.46 \pm 0.08$ | $0.40 \pm 0.05$ | $3.25 \pm 0.15$ | $23.56 \pm 0.02$ | $24.64 \pm 0.06$ | $4956$ | $68.7 \pm 2.3$ | $144 \pm 13$ | $9.06 \pm 0.06$ | $8.02 \pm 0.11$ | $10.87 \pm 3.19$ | $0.80 \pm 0.03$ |
| 198457  | 09:53:00     | +07:15:22    | $-16.79 \pm 0.06$ | $0.16 \pm 0.04$ | $4.35 \pm 0.13$ | $22.54 \pm 0.02$ | $24.03 \pm 0.04$ | $6457$ | $97.0 \pm 2.3$ | $117 \pm 12$ | $9.20 \pm 0.06$ | $8.06 \pm 0.08$ | $13.81 \pm 3.20$ | $0.87 \pm 0.01$ |
| 202262  | 10:37:29     | +12:23:46    | $-14.58 \pm 0.24$ | $0.22 \pm 0.03$ | $1.99 \pm 0.22$ | $22.95 \pm 0.01$ | $24.31 \pm 0.02$ | $1330$ | $22.0 \pm 2.4$ | $59 \pm 4$ | $8.35 \pm 0.10$ | $7.29 \pm 0.11$ | $11.40 \pm 3.90$ | $0.85 \pm 0.01$ |
| 215226  | 11:43:32     | +15:02:33    | $-14.79 \pm 0.12$ | $0.33 \pm 0.05$ | $1.92 \pm 0.11$ | $22.69 \pm 0.02$ | $24.14 \pm 0.04$ | $2970$ | $45.0 \pm 2.3$ | $86 \pm 12$ | $8.33 \pm 0.07$ | $7.62 \pm 0.11$ | $5.14 \pm 1.51$ | $0.86 \pm 0.01$ |
| 219242  | 11:29:39     | +07:47:36    | $-16.77 \pm 0.06$ | $0.30 \pm 0.04$ | $4.28 \pm 0.14$ | $22.33 \pm 0.02$ | $24.04 \pm 0.04$ | $6230$ | $94.1 \pm 2.4$ | $150 \pm 8$ | $9.26 \pm 0.06$ | $8.34 \pm 0.08$ | $8.39 \pm 1.90$ | $0.90 \pm 0.01$ |
| 223141  | 12:41:12     | +10:55:58    | $-16.90 \pm 0.06$ | $0.28 \pm 0.03$ | $5.67 \pm 0.17$ | $22.95 \pm 0.01$ | $24.06 \pm 0.03$ | $6479$ | $97.2 \pm 2.3$ | $145 \pm 1$ | $9.49 \pm 0.05$ | $8.34 \pm 0.07$ | $13.99 \pm 2.82$ | $0.80 \pm 0.01$ |
| 321194  | 22:57:04     | +25:43:30    | $-14.98 \pm 0.29$ | $0.36 \pm 0.02$ | $1.54 \pm 0.21$ | $22.78 \pm 0.01$ | $24.06 \pm 0.02$ | $1050$ | $16.5 \pm 2.2$ | $95 \pm 2$ | $8.48 \pm 0.12$ | $7.76 \pm 0.12$ | $5.27 \pm 2.07$ | $0.86 \pm 0.01$ |
| 729579  | 11:24:17     | +25:42:38    | $-13.94 \pm 0.21$ | $0.21 \pm 0.04$ | $1.86 \pm 0.18$ | $23.23 \pm 0.02$ | $24.74 \pm 0.04$ | $1523$ | $25.4 \pm 2.4$ | $85 \pm 3$ | $8.50 \pm 0.09$ | $7.02 \pm 0.12$ | $30.02 \pm 10.24$ | $0.87 \pm 0.01$ |
| 749223  | 11:54:45     | +26:00:18    | $-14.80 \pm 0.11$ | $0.02 \pm 0.05$ | $2.18 \pm 0.12$ | $23.16 \pm 0.02$ | $24.25 \pm 0.04$ | $2968$ | $45.0 \pm 2.3$ | $86 \pm 7$ | $8.49 \pm 0.07$ | $6.98 \pm 0.11$ | $32.67 \pm 9.88$ | $0.79 \pm 0.01$ |
| 749493  | 15:05:09     | +24:02:04    | $-16.23 \pm 0.08$ | $0.28 \pm 0.03$ | $4.15 \pm 0.16$ | $22.58 \pm 0.01$ | $24.27 \pm 0.03$ | $4245$ | $64.2 \pm 2.2$ | $138 \pm 7$ | $9.16 \pm 0.06$ | $8.07 \pm 0.07$ | $12.19 \pm 2.51$ | $0.89 \pm 0.01$ |

Notes. Errors of $M_g$ are rms errors obtained by SExtractor. Errors of $\mu_{g,0,\text{edge}}$ and $r_e$ are obtained by GALFIT. Errors of H I mass, distance, and $W_{50}$ are from the $\alpha.40$ catalog, and the other errors are calculated by error propagation functions.

$^a$ Absolute magnitude is calculated from photometry using SExtractor and distance is from the $\alpha.40$ catalog.

$^b$ Observational edge-on perspective central surface brightness obtained from GALFIT fitting with an edge-on disk model with correction of cosmological dimming effects.

$^c$ Face-on perspective central surface brightness corrected from observed edge-on values by a factor of $2.5lg(h_i/r_e)$.

$^d$ Dist, $W_{50}$, and H I mass are achieved directly from the $\alpha.40$ catalog.

$^e$ Stellar mass calculated using the g-band parameters in the work of Zibetti et al. (2009) and $g - r$ color.

$^f$ Ellipticity of HUDS candidates ($1 - \frac{a}{b}$).
fainter than for face-on galaxies, with the standard deviation (Figure 3. The Astrophysical Journal, dots) large uncertainties might be involved with the magnitudes of internal extinction of edge-on galaxies may generally not differ much from the low-luminosity face-on galaxies.

obtain the $A_g$:

$$E(B-V) = \frac{1.086/R_v}{A_v} \ln\left(\frac{H_\alpha/H_\beta}{H_{\alpha 0}/H_{\beta 0}}\right)$$

For the galaxies that have $A_g < 0$, we assume they have $A_g = 0$. Finally, we plot the derived extinction $A_g$ of edge-on (red dots) and face-on (blue dots) galaxies in the Figure 3. As shown in the figure, an obvious systematic offset between the extinction of the edge-on and face-on galaxies does not appear to exist.

After deriving the dust extinction value of edge-on and face-on galaxies, we further compare the dust extinction value between edge-on and face-on galaxies. Statistically, the mean values of $A_g$ are 0.10 mag for edge-on galaxies and 0.08 mag for face-on galaxies, with the standard deviation ($\sigma$) of 0.08 mag for edge-on galaxies and 0.07 mag for face-on galaxies. The difference between the mean extinction values of edge-on and face-on galaxies is 0.02 mag, which is much smaller than the standard deviations. This indicates that the internal extinction of edge-on galaxies may generally not differ much from that of face-on galaxies in terms of statistics. If we insist on correcting the dust extinction for edge-on galaxies, large uncertainties might be involved with the magnitudes of edge-on galaxies. Also, as Giovanelli et al. (1995), Masters et al. (2003, 2010), Maller et al. (2009), and Devour & Bell (2016) discuss, with the decrease in luminosity of galaxies, the attenuation parameter $\gamma$ declines and the variety of relative extinction in the $g$ band flattens. This suggests that low-luminosity galaxies tend to have low extinction. Thus, we decide not to correct the internal extinction of our edge-on galaxies.

4. Properties of HUDS Candidates

We list some major parameters of our 11 HUDS candidates in Table 1. In this table, the AGC ID is the entry number in the Arecibo General Catalog (AGC) (Haynes et al. 2011) and the R.A., decl., distance, velocity width $W_{50}$, and H I mass are from the $\alpha$.40 catalog. $r_{g, e}$ and $\mu_{g, 0, edge}$ are derived from the GALFIT edge-on disk model fitting, while $\epsilon = 1-b/a$ and $b/a$ are derived from the GALFIT fitting with an exponential disk model. $\mu_{g, 0, face}$ is the face-on perspective central surface brightness corrected from $\mu_{g, 0, edge}$ by Equation (5). Stellar mass ($M_*$) is calculated using the method of Zibetti et al. (2009) with $M_*$ and $g-r$ color.

Figure 4 shows the distributions of general properties (central surface brightness $\mu_{g, 0}$, effective radius $r_e$, absolute magnitude $M_g$, $g-r$ color, mass ratio $M_H/M_*$, H I mass, velocity width $W_{50}$, and ellipticity) of 11 HUDS candidates and other comparison UDGs. The compared UDGs are from the sample of isolated HUDS of $\alpha$.70 (L17) and those in groups and clusters are from other works (V15a Merritt et al. 2016; Román & Trujillo 2017b; Shi et al. 2017; Müller et al. 2018)

Our HUDS candidates are from the optical-H I cross-matches between SDSS DR7 and $\alpha$.40 (Haynes et al. 2011), while the L17 HUDS are from the cross-matches between SDSS DR12 and $\alpha$.70. For comparison, we additionally compare the whole L17 HUDS R (purple lines) sample with HUDS that are both included in the L17 HUDS R sample and optical-H I cross-matches between SDSS DR7 and $\alpha$.40 (blue lines). The HUDS R sample is selected with strict criteria of $\mu_{g, 0} > 24$ mag arcsec$^{-2}$ and $r_{g, e} > 1.5$ kpc, while the HUDS B sample is selected by $\langle \mu_{g, ext} \rangle > 24$ mag arcsec$^{-2}$ and $r_{g, e} > 1.5$ kpc, broader than HUDS R. As Figure 4 shows, there is no significant difference for the distribution of properties between the total HUDS_R sample and its $\alpha$.40 part. It seems that despite a difference in amounts, it will not take a significant difference in the distributions of properties between the $\alpha$.40 and $\alpha$.70 catalogs, as seen for SDSS DR7 and SDSS DR12.

4.1. Optical Properties

The absolute magnitudes $M_g$ of our edge-on HUDS candidates range from $-14$ to $-17$ mag and the effective radii $r_e$ are from 1.5 to 5.67 kpc. Both are consistent with those of the HUDS_R sample of L17. Also, the edge-on HUDS candidates are very blue and the average color of $g-r$ is 0.26, even bluer than that of 0.344 for the HUDS_R sample. But all the $g-r$ colors of edge-on HUDS are still in the range of the HUDS_R sample. All these optical properties of edge-on HUDS candidates are similar to those of the HUDS_R sample, and the blue colors of edge-on HUDS candidates also indicate that it is reasonable to neglect internal extinction of edge-on HUDS.

However, we also make a comparison of ellipticity with other UDGs in Figure 4(h). As our candidates are all edge-on, the $g$-band ellipticity values of our HUDS candidates are all larger than 0.79, and their mean value is 0.85. The largest values of ellipticity for UDGs in the group (Merritt et al. 2016; Román & Trujillo 2017b; Shi et al. 2017; Müller et al. 2018) and UDGs in the Coma cluster (V15a) are 0.7 and 0.62, while their mean values are 0.31 and 0.28, respectively. It is obvious that the ellipticity values of our HUDS candidates are really much larger than those of other UDGs. Because the $b/a$ or ellipticity of L17 were not available, we have not compared with L17. However, we have cross-matched the HUDS_B sample with our 1670 edge-on subsample, which are selected by $b/a \leq 0.3$ (mentioned in Section 1), and no galaxy was matched. Thus, the edge-on HUDS that we found have not
been included in the HUDS_B sample. By checking the DECaLS images of the HUDS sample, which are deeper than SDSS images, the morphologies of the HUDS_B sample seem less likely to be high-inclination galaxies.

4.2. Stellar Mass Estimates

There are many methods that use optical colors to estimate stellar mass to light ratios (e.g., Bell et al. 2003; Zibetti et al. 2009; Taylor et al. 2011; Into & Portinari 2013; McGaugh & Schombert 2014; Roediger & Courteau 2015). But in some situations, there may be significant variance of stellar mass estimated by different methods because of the dependence on SFH, initial mass function, and assumption of extinction (Conroy 2013; McGaugh & Schombert 2014; Herrmann et al. 2016; García-Benito et al. 2019). Román & Trujillo (2017b) uses the method provided by Roediger & Courteau (2015) to obtain a rough stellar mass. Also Roediger & Courteau (2015) provide two SPS model results, BC03 (Bruzual & Charlot 2003) and FSPS (Conroy et al. 2009). This may be especially true for low-surface-brightness sources with extreme stellar populations. While L17 use the Z09 method for three sources with H I-synthesis observations, Martínez-Delgado et al. (2016) give a comparison between Zibetti et al. (2009), hereafter Z09 and Bell et al. (2003, hereafter Bell03) for a single UDG in a much lower-density environment, and conclude that Bell03 may be a factor of two higher than Z09.

So we estimate the stellar mass using all the methods mentioned above, Z09, Bell03, BC03 and FSPS, and compare their results to see whether the different methods lead to a different conclusion. The results are displayed in Table 2. A comparison shows that the lowest stellar masses of these sources occur when applying Z09, and the largest ones occur when employing Bell03. The latter can be a factor of two higher than Z09, which is what was observed in Martínez-Delgado et al. (2016). But even if using Bell03, the ratios of $M_\text{HI}$ and $M_*$ also imply that our HUDS candidates are gas-rich galaxies. In addition, no matter which method has been chosen, the results for stellar mass are not beyond the range of stellar mass for the UDGs of Koda et al. (2015). To compare our results with L17, we finally adopt the Z09 method to calculate stellar mass, and the following discussion is also based on it. In this method,

$$l_g \left( \frac{M}{M_\odot} \right) = a_\lambda + \left( b_\lambda \times \text{color} \right)$$

and we use the $g$-band and $g - r$ color for calculation, and the $a_\lambda$ and $b_\lambda$ are $-1.030$ and $2.053$, respectively. The stellar mass of our HUDS candidates ranges from $10^{6.98} M_\odot$ to $10^{8.35} M_\odot$, which is included in the range of L17.

4.3. H I Properties

All the H I information for our HUDS candidates is derived from $\alpha_{40}$, as shown in Figures 4(e)-(g).

The distributions of stellar mass and H I mass for our edge-on HUDS candidates demonstrate that they have H I masses of $10^{8.33} M_\odot \sim 10^{9.49} M_\odot$, which are much larger than their stellar mass. Based on their stellar mass, they are optical dwarf galaxies, but they have the medium mass of H I gas ($7.7 \leq l_g(M_{HI}) \leq 9.5$), according to the classification of Huang et al. (2012).
Table 2
Stellar Masses from Using Different Methods

| AGCNr  | $lg(M_\text{HI}/M_\odot)$ | $lg(M_*/M_\odot)$ (Bell03)$^a$ | $lg(M_*/M_\odot)$ (BC03)$^b$ | $lg(M_*/M_\odot)$ (FSPS)$^c$ | $M_\text{HI}/M_*$ (Bell03) | $M_\text{HI}/M_*$ (BC03) | $M_\text{HI}/M_*$ (FSPS) | $M_\text{HI}/M_*$ (Z09)$^d$ |
|--------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 102276 | 9.10 ± 0.06     | 8.69 ± 0.04     | 8.38 ± 0.05     | 8.51 ± 0.05     | 8.35 ± 0.05     | 2.58 ± 0.44     | 5.21 ± 0.96     | 3.89 ± 0.71     | 5.68 ± 1.05     |
| 113816 | 9.06 ± 0.06     | 8.34 ± 0.09     | 8.06 ± 0.11     | 8.18 ± 0.10     | 8.02 ± 0.11     | 5.26 ± 1.27     | 9.99 ± 2.91     | 7.58 ± 2.11     | 10.87 ± 3.19    |
| 198457 | 9.20 ± 0.06     | 8.51 ± 0.06     | 8.10 ± 0.08     | 8.25 ± 0.08     | 8.06 ± 0.08     | 4.95 ± 0.98     | 12.53 ± 2.88    | 8.83 ± 1.95     | 13.81 ± 3.20    |
| 202262 | 8.35 ± 0.10     | 7.71 ± 0.10     | 7.33 ± 0.11     | 7.48 ± 0.11     | 7.29 ± 0.11     | 4.37 ± 1.45     | 10.38 ± 3.54    | 7.44 ± 2.52     | 11.40 ± 3.90    |
| 215226 | 8.33 ± 0.07     | 7.97 ± 0.08     | 7.66 ± 0.11     | 7.79 ± 0.10     | 7.62 ± 0.11     | 2.28 ± 0.57     | 4.71 ± 1.37     | 3.50 ± 0.98     | 5.14 ± 1.51     |
| 219242 | 9.26 ± 0.06     | 8.71 ± 0.06     | 8.38 ± 0.08     | 8.51 ± 0.07     | 8.34 ± 0.08     | 3.56 ± 0.69     | 7.67 ± 1.72     | 5.64 ± 1.22     | 8.39 ± 1.90     |
| 223141 | 9.49 ± 0.05     | 8.73 ± 0.06     | 8.38 ± 0.07     | 8.52 ± 0.07     | 8.34 ± 0.07     | 5.76 ± 0.99     | 12.78 ± 2.55    | 9.33 ± 1.79     | 13.99 ± 2.82    |
| 321194 | 8.48 ± 0.12     | 8.10 ± 0.12     | 7.80 ± 0.12     | 7.92 ± 0.12     | 7.76 ± 0.12     | 2.42 ± 0.94     | 4.84 ± 1.90     | 3.63 ± 1.42     | 5.27 ± 2.07     |
| 729579 | 8.50 ± 0.09     | 7.44 ± 0.10     | 7.06 ± 0.12     | 7.21 ± 0.11     | 7.02 ± 0.12     | 11.43 ± 3.61    | 27.32 ± 9.28    | 19.54 ± 6.51    | 30.02 ± 10.24   |
| 749223 | 8.49 ± 0.07     | 7.50 ± 0.09     | 7.02 ± 0.11     | 7.19 ± 0.10     | 6.98 ± 0.11     | 9.88 ± 2.55     | 29.42 ± 8.84    | 19.86 ± 5.74    | 32.67 ± 9.88    |
| 749493 | 9.16 ± 0.06     | 8.46 ± 0.05     | 7.11 ± 0.07     | 8.25 ± 0.06     | 8.07 ± 0.07     | 5.04 ± 0.93     | 11.13 ± 2.28    | 8.13 ± 1.62     | 12.19 ± 2.51    |

Notes.

$^a$ Stellar mass computed using the mass-to-light versus color relations of Bell et al. (2003).

$^b$ Stellar mass computed using the mass-to-light versus color relations in Table A1 of Roediger & Courteau (2015).

$^c$ Stellar mass computed using the mass-to-light versus color relations in Table A1 of Roediger & Courteau (2015).

$^d$ Stellar mass computed using the mass-to-light versus color relations of Zibetti et al. (2009).
As Figure 4(e) demonstrates, our HUDS candidates are gas-rich galaxies, and their H I-to-stellar mass ratios are from 5.14 to 32.67. The most gas-rich edge-on HUDS is AGC 749223. Its H I mass is \( \sim 33 \) times stellar mass. The comparison samples in Figure 4(e) are the HUDS_BG sample (green line), which is cross-matched with the sample of Huang et al. (2012), and the five blue UDGs (orange line), which are found in Hickson Compact Groups (HCGs) by Román & Trujillo (2017b), are taken from H1 observations by GBT and VLA (Spekkens & Karunakaran 2018). From this figure, the mass ratio distributions of our HUDS candidates and HUDS_BGs are similar, and are larger than those of the five blue UDGs found in groups.

The velocity widths (\( W_{}\alpha \)) of our edge-on HUDS candidates are from 59 to 150 km s\(^{-1}\), which is much larger than those of the HUDS_R sample. This can be explained as the effect of inclination.

### 4.4. Environment

To examine the environment of our HUDS candidates, we also employ the criteria applied by L17 to check whether they are isolated sources. The requirement is that the nearest galaxy, which has a heliocentric velocity within 500 km s\(^{-1}\), must have a projected separation farther than 350 kpc. As L17 utilized a private catalog, the AGC, we use both SDSS DR15 and the 100% ALFALFA catalog instead. In this method, the first nearest neighbor only probes the local environment, and we have not examined the large-scale environments of these HUDS candidates.

We find out that there are three HUDS (AGC 202262, AGC 215226, and AGC 729579) that have one nearby galaxy according to this criterion, and one HUDS (AGC 219242) has two neighbors. A nearby galaxy is not found to satisfy the criterion for the other candidates. So, our HUDS candidates are in low-density environments, and 64% of them are isolated galaxies. To understand this result clearly, we list all the nearby neighbors of the four HUDS candidates (AGC 202262, AGC 215226, AGC 219242, and AGC 729579), and the nearest galaxy of other HUDS candidates, which do not satisfy the criteria, in Table 3. As Du et al. (2015) compared the environment of H I-selected non-edge-on low-surface-brightness galaxies with all the galaxies from the 40% ALFALFA catalog, they are both more likely to reside in local low-density environments. We also try to get the fraction of isolated galaxies from the 100% ALFALFA catalog using the criteria mentioned in the Section 2.1 of L17, and obtain a value of \( \sim 65\% \), which is similar to the proportion of isolated galaxies in our HUDS candidates. Similar to all the galaxies from the entire ALFALFA catalog, our HUDS candidates selected from the \( \alpha.40 \) catalog also inhabit the local low-density environment.

As both our edge-on HUDS candidates and the HUDS_R sample are in low-density environments, and have similar properties, it is very possible that our HUDS candidates complement the HUDS_R sample. Compared with our edge-on HUDS candidates, though UDGs in clusters from V15a have a similar distribution of effective radius, they have fainter central surface brightness and lower absolute magnitudes (Figures 4(a)–(c)). Also, UDGs in clusters have a red color of \( g-r \sim 0.6 \) (van der Burg et al. 2016) on average. Therefore, UDGs in the field and in clusters are quite different populations.

### 5. Discussion

#### 5.1. Sample Uncertainty

While current measurements result in a sample of 11 edge-on candidate HUDS, uncertainties in the measured parameters may have some impact on the size of the sample. If considering the measurement errors in Table 1, there may be three objects that do not satisfy the criteria of \( \mu_{\alpha,0} \geq 24 \). As for the internal extinction in Section 3.3, if we correct the difference of 0.02 between edge-on and face-on galaxies, 10 out of our 11 HUDS candidates will still satisfy our definition of UDGs; if we consider the standard deviation of edge-on internal extinction 0.08, 6 out of our 11 HUDS candidates will still meet our definition of UDGs.
5.2. Inclination Selection Effect

With an equal total luminosity, like $M_r$, the observed central surface brightness $\mu_{g,0}$ of an edge-on disk-like galaxy is brighter than that of a face-on galaxy. If a face-on galaxy has $\mu_{g,0,\text{face}} = 24$ mag arcsec$^{-2}$ and $h_l/r_s = 0.3$, its observed central surface brightness will become $\mu_{g,0,\text{edge}} = 22.69$ when it turns to an edge-on perspective, and then it will be missed by the criteria for UDG. Also, for the observed galaxies that satisfy the $\mu_{g,0}$ criterion of $\mu_{g,0} \geq 24$ mag arcsec$^{-2}$, the edge-on galaxies should have much lower luminosity than face-on galaxies, and also have less morphological characteristics that appear in images. This makes the edge-on galaxies become more difficult to detect. Therefore, it may lose many edge-on galaxies, which have a disk galaxy profile. Just like our edge-on HUDS candidates, they have not been found in L17. So it is very possible that there is a selection effect for searching disk-like UDGs, like Figure 4(h) illustrates. Maybe that is why there is not a sufficient edge-on UDG subpopulation in L17, V15a and many other works. However, this inclination selection effect mainly influences exponential disk profile galaxies, and would decrease with the increase of Sérsic index, and can be neglected for irregular galaxies.

5.3. Mechanism of UDG Candidates

The UDGs in clusters could be explained by failed $L_*$ galaxies (V15a), regular or irregular dwarf galaxies (Amorisco & Loeb 2016; Beasley et al. 2016; Beasley & Trujillo 2016), and tidal dwarfs (van Dokkum et al. 2018). However, the low-density environments and regular morphology of these edge-on HUDS candidates selected from $\alpha_{40}$ indicate that they are less likely to be tidal dwarfs. Also, the dwarf irregular galaxy is not a good explanation for our sources, as most of our HUDS candidates are disk-like galaxies. Although our HUDS candidates have an H1 mass of $\log(M_{\text{H1}}/M_\odot)$ from 8.33 to 9.5, the low-surface-density environment and low star-formation efficiency make them difficult to transform H1 gas to stars. Their slow evolution would be the key reason that they only have small stellar mass like dwarf galaxies. Even if all the H1 gas can be transformed to stars, their stellar masses are still far less than the stellar mass of $\sim 5 \times 10^{10}$ of $L_*$ galaxies. Our edge-on HUDS candidates are medium-mass disk-like UDGs and cannot be explained by failed $L_*$ galaxies.

Figure 5 shows the color–absolute magnitude diagram of UDGs in fields and clusters, and the big black star is a rough mean value of UDGs in the Coma cluster (V15a). The red solid line is the dividing line to separate the red and blue sequence galaxies (van der Burg et al. 2015) at a redshift of 0.013 (mean redshift of our HUDS) and the red dashed line is the fitting line of UDGs in clusters (van der Burg et al. 2016). This figure shows that all of our HUDS candidates and most HUDS_R separate from UDGs in clusters.

Based on the ALFALFA 40% catalog and SDSS-DR7 $g$-/$r$-band images, we have selected 11 edge-on HUDS candidates after correcting the edge-on central surface brightness to face-on central surface brightness. All of these edge-on HUDS candidates are very blue and H1-bearing, mostly isolated from nearby neighbors, and have properties consistent with those HUDS from the ALFALFA 70% catalog (L17). In this paper, we focus on the detection of edge-on disk-like UDGs. These sources may be excluded by the criteria used to find UDGs if authors do not correct their central surface brightness values, but they can be easier to detect with an equal total magnitude, and they are good for studying their rotational velocity. We can improve the population of UDGs at the high-inclination tail using the correction of $\mu_{g,0}$. Also, the consistency of the properties between our HUDS candidates and HUDS detected from (L17) demonstrates that our approach is an efficient and reasonable way to select UDGs from edge-on systems.

Figure 5. Color–absolute magnitude diagram of UDGs in fields and clusters. Green filled circles are our 11 edge-on HUDS candidates in $\alpha_{40}$, blue triangles are HUDS_R of L17, orange diamonds are the complete group of UDGs found by Román & Trujillo (2017), Müller et al. (2018), and Merritt et al. (2016), and the big black star is a rough mean value of UDGs in the Coma cluster (V15a). The red solid line is the dividing line to separate the red and blue sequence galaxies (van der Burg et al. 2015) at a redshift of 0.013 (mean redshift of our HUDS) and the red dashed line is the fitting line of UDGs in clusters (van der Burg et al. 2016). This figure shows that all of our HUDS candidates and most HUDS_R separate from UDGs in clusters.

6. Summary

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