The Isophotal Structure of Star-forming Galaxies at $0.5 < z < 1.8$ in CANDELS: Implications for the Evolution of Galaxy Structure

Dongfei Jiang1,2, F. S. Liu1,3, Xianzhong Zheng2,4, Hassen M. Yesuf3, David C. Koo3, S. M. Faber3, Yicheng Guo3, Anton M. Koekemoer5, Weichen Wang6, Jerome J. Fang3,7, Guillermo Barro3,8, Xianmin Meng9, Dale Kocevski10, Elizabeth J. McGrath10, and Nimish P. Hathi11,12

1 College of Physical Science and Technology, Shenyang Normal University, Shenyang 110034, People’s Republic of China; fengshan.liu@yahoo.com
2 Chinese Academy of Sciences South America Center for Astronomy, China-Chile Joint Center for Astronomy, Camino El Observatorio 1515, Las Condes, Santiago, Chile
3 University of California Observatories and the Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA
4 Chinese Academy of Sciences South America Center for Astronomy, China-Chile Joint Center for Astronomy, Camino El Observatorio 1515, Las Condes, Santiago, Chile
5 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
6 Department of Physics & Astronomy, Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218, USA
7 Albert Einstein College of Medicine, 1300 Morris Park Avenue, Bronx, NY 10461, USA
8 Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA
9 National Astronomical Observatories, Chinese Academy of Sciences, A20 Datun Road, Beijing 100012, People’s Republic of China
10 Department of Physics and Astronomy, Colby College, Mayflower Hill Drive, Waterville, ME 04901, USA
11 Aix Marseille Université, CNRS, LAM (Laboratoire d’Astrophysique de Marseille) UMR 7326, F-13388, Marseille, France

Received 2017 April 23; revised 2018 January 4; accepted 2018 January 4; published 2018 February 13

Abstract

We have measured the radial profiles of isophotal ellipticity ($\varepsilon$) and disky/boxy parameter $A_4$ out to radii of about three times the semimajor axes for ~4600 star-forming galaxies (SFGs) between redshift $0.5$ and $1.8$ in the CANDELS/GOODS-S and UDS fields. Based on the average size–mass relation in each redshift bin, we divide our galaxies at a given mass into Small SFGs (SSFGs; smaller than the average) and Large SFGs (LSFGs; larger than the average). We show that, at low masses ($M_* < 10^{10} M_{\odot}$), the SSFGs generally have nearly flat $\varepsilon$ and $A_4$ profiles in both edge-on and face-on views, especially at $z > 1$. Moreover, the median $A_4$ values at all radii are almost zero. In contrast, the highly inclined low-mass LSFGs in the same mass-redshift bins generally have monotonically increasing $\varepsilon$ profiles with radius and disky feature dominated in the intermediate regions. These findings imply that at these redshifts, the low-mass LSFGs are not disk-like, whereas the low-mass LSFGs likely harbour disk-like components flattened by significant rotations. At high masses ($M_* > 10^{10} M_{\odot}$), both highly inclined SSFGs and LSFGs generally exhibit distinct trends in both $\varepsilon$ and $A_4$ profiles, which increase as one moves to lower redshifts. This feature is more prevalent for more massive ($M_* > 10^{10.5} M_{\odot}$) galaxies or at lower redshifts ($z < 1.4$). This feature can be simply explained if galaxies possess all three components: central bulges, disks in the intermediate regions, and halo-like stellar components in the outskirts.

Key words: galaxies: high-redshift – galaxies: photometry – galaxies: star formation

1. Introduction

In the $\Lambda$CDM framework of hierarchical growth of structures, galaxies are built up by mergers and low-mass accretion events (e.g., Eggen et al. 1962; Sandage 1986; Purcell et al. 2007; De Lucia & Helmi 2008; Johnston et al. 2008; Cooper et al. 2013; Pillepich et al. 2014). Stars stripped from infalling satellite galaxies build up a diffuse and highly structured stellar halo surrounding the central galaxy, which, as a consequence of the relatively long dynamical timescales in the outskirts of galaxies, retains a “memory” of past accretion events (e.g., Eggen et al. 1962; Searle & Zinn 1978; Steinmetz & Muller 1995; Bekki & Chiba 2001; Samland & Gerhard 2003).

The past decade has seen tremendous advances in our understanding of the formation and evolution of bulges (see Tonini et al. 2016a, 2016b, for reviews). Bulges are now divided into two main categories: classical bulges and pseudo-bulges (Kormendy 1993; Kormendy & Kennicutt 2004). The classical bulges, resembling elliptical galaxies, are dynamically hot spheroids with stellar motions dominated by velocity dispersion rather than rotation and usually have a strongly concentrated structure (e.g., Sérsic index $n \sim 4$). The pseudo-bulges are more dynamically cold and exhibit intermediate features (e.g., in Sérsic index and velocity dispersion) between classical bulges and highly inclined (oblate) disks. Another prevalent feature of pseudo-bulges is the disky shape, which spurred Kormendy & Illingworth (1982) to suggest that secular processes are responsible for the formation of pseudo-bulges.

Better understanding of the formation of bulges requires quantifying the relative importance of different channels of galaxy evolution such as merger-driven and secular processes (Kormendy & Kennicutt 2004). Recently, the instabilities in disks (e.g., Krumholz & Burkert 2010; Bournaud et al. 2011; Cacciato et al. 2012; Forbes et al. 2012) and mass transfer from unstable disks have been examined as bulge build-up mechanisms, in particular in disk galaxies at high redshifts (e.g., Noguchi 1999; Elmegreen et al. 2008; Dekel et al. 2009; Hathi et al. 2009; Genzel et al. 2011; Forbes et al. 2014). More recently, Tonini et al. (2016a) predicted two distinct populations of bulges: merger-driven bulges, akin to classical bulges, and instability-driven bulges, akin to pseudo-bulges. Huertas-Company et al. (2015) also proposed two distinct channels for the growth of bulges in massive galaxies. Huertas-Company...
et al. (2015) showed that around one-third of the bulge population in massive galaxies formed at early epochs (before \( z \sim 2.5 \)) through gas-rich mergers or violent disk instabilities, which usually have high Sérsic indices (\( n > 3-4 \)) and small effective radii (\( \sim 1 \) kpc). The remaining two-thirds underwent a gradual morphological transformation at late epochs, from clumpy disks to more regular bulge+disk systems, resulting in a significant growth of bulge components with low Sérsic indices (\( n < 3 \)). If secular evolution is a more important process in shaping the bulge population at late epochs, the build-up of bulges in lockstep with disk growth should be observed.

Fairly large and massive spiral galaxies such as the Milky Way (MW) often have extended stellar halos. The stellar halo of the Milky Way has been well characterized (see a review by Helmi 2008). Recent advances in observation have also enabled the detection of faint stellar halos around external galaxies, such as M31 (Ferguson et al. 2002; Guhathakurta et al. 2005; Irwin et al. 2005; Ibata et al. 2007) and other nearby disk galaxies (Mouhcine et al. 2005a, 2005b; de Jong et al. 2007; Ibata et al. 2009; Mouhcine et al. 2010). The observed properties of the stellar halos in the Milky Way and its neighboring galaxies are in general agreement with the predictions of the ΛCDM hierarchical galaxy formation models (Bell et al. 2008; Gilbert et al. 2009; McConnachie et al. 2009; Starkenburg et al. 2009; Martínez-Delgado et al. 2010). Cosmological simulations predict that the amount of stellar mass in these halos should be \( \sim 10^8-10^9 M_\odot \) for MW-like galaxies, and most of the stellar halo mass would be assembled before \( z \sim 1 \) (De Lucia & Helmi 2008; Cooper et al. 2010; De Lucia 2012, for a review).

However, the detection of stellar halos in distant disk galaxies has rarely been reported to date. The lack thereof has stemmed progress in understanding the early formation and assembly histories of disk galaxies. For instance, we know of only two works that detected stellar halos beyond \( z = 0.3 \) (Zibetti & Ferguson 2004; Trujillo & Bakos 2013). Both works took advantage of the deep high-resolution \( HST \) imaging in \( Hubble Ultra Deep Field \) (Beckwith et al. 2006). Zibetti & Ferguson (2004) detected the stellar halo of a disk galaxy at \( z = 0.32 \), while Trujillo & Bakos (2013) detected the stellar halos of two MW-like galaxies at \( z \sim 1 \). Thanks to the large galaxy sample in the Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey (CANDELS; Grogan et al. 2011; Koekemoer et al. 2011), with \( HST \) imaging, we now can detect and investigate the stellar halos at intermediate and high redshifts in a statistical manner and significantly advance our understanding of the assembly histories of disk galaxies.

In local galaxies, it has been well established that the isophotal shapes of galaxies are coupled with their structural and kinematic properties. The isophotes of spheroids often deviate from pure ellipses. These deviations originate from the characteristics of the stellar orbits that make up these galaxies. The correlations between the isophotal deviations and physical properties of galaxies were shown mostly for nearby early-type galaxies (e.g., Carter 1978; Lauer 1985; Bender et al. 1988, 1989; Hao et al. 2006) and for few late-type galaxies (e.g., Erwin & Debattista 2013).

In addition to the isophotal deviations, the ellipticity (\( 1—\)axis ratio) of a galaxy has been shown to be closely linked with the relative importance of rotation and random motion in spheroids (Kormendy 2013). Furthermore, the ellipticity is linked to the isophotal deviations themselves (Hao et al. 2006). Generally, more flattened systems (with larger ellipticities) tend to be more rotationally supported and have more disky isophotal shapes. Therefore, a combined radial profile analysis of the isophotal ellipticity and deviations is likely helpful diagnostic of the kinematics and morphological compositions of galaxies. For example, in nearly edge-on view, disk galaxies are more prominently flattened and have more disky isophotal shapes than galaxies dominated by central bulges or outer stellar halos (Zheng et al. 2015).

Furthermore, quantifying the variation of the isophotal shape profile across cosmic time may provide key insights on the evolution of galaxy structure. Using the deep high-resolution \( HST/WFC3 \) imaging data, we measure the radial profiles of isophotal ellipticity (\( \epsilon \)) and deviation parameter \( A_4 \) (defined in Section 3) for \( \sim 4600 \) \( UVJ \)-defined star-forming galaxies (SFGs) at \( 0.5 < z < 1.8 \) selected from the CANDELS/GOODS-S and UDS fields. The isophotal shape profiles have been securely determined out to large radii of about three times semimajor axes for more than two-thirds of the galaxies in our sample. This has enabled, for the first time, statistically robust profile analyses of the isophotal shapes out to large radii in distant SFGs. We study the stacked (median) \( \epsilon \) and \( A_4 \) profiles of our galaxies sub-divided by stellar mass and redshift. We also sub-divide our galaxies into Small and Large SFGs based on the relative size difference to the average size–mass relation. We show that, statistically, the two classes of SFGs exhibit difference in the profiles of the isophotal shape parameters.

The outline of this paper is as follows. In Section 2, we describe the data and the sample selection. In Section 3, we describe the measurement of isophotal shape profiles. We present our main

### Table 1

| Cut                        | GOODS-S | UDS | Combined |
|-----------------------------|---------|-----|----------|
| Full catalog                | 34,930  | 35,932 | 70,862   |
| \( F160W < 24.5 \)          | 8293    | 9671 | 17,964   |
| \( SE_{\text{PhotFlag}} = 0 \) | 8104    | 9151 | 17,255   |
| \( SE_{\text{CLASS,STAR}} < 0.9 \) | 7891    | 8933 | 16,824   |
| \( 0.5 < z < 1.8 \)        | 4753    | 5735 | 10,488   |
| \( 9.0 < \log M^* < 11.0 \) | 3261    | 3964 | 7225     |
| \( \text{GALFIT flag} = 0 \) | 2868    | 3555 | 6423     |
| \( ISO_{\text{PhotFlag}} = 0 \) | 2690    | 3434 | 6124     |
| \( R_{\text{MAD}} > 0.18 \) | 2250    | 2829 | 5079     |
| \( UVJ\text{-defined SFGs} \) | 2036    | 2571 | 4607     |
| non-compact SFGs            | 2033    | 2562 | 4595     |

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results in Section 4 and finish with a discussion and summary in Section 5. Throughout the paper, we adopt a cosmology with \( \Omega_m = 0.3 \), \( \Omega_{\Lambda} = 0.7 \) and \( H = 70 \) km s\(^{-1}\) Mpc\(^{-1}\). All magnitudes are in the AB system.

## 2. Data and Sample Selection

### 2.1. Data

The sample of galaxies used in this work is selected from the CANDELS/GOODS-S and UDS fields (Grogin et al. 2011; Koekemoer et al. 2011). Multi-wavelength photometry catalogs of the two fields were built by the former works of the CANDELS team (Galametz et al. 2013; Guo et al. 2013). The reader is referred to Guo et al. (2013, for GOODS-S) and Galametz et al. (2013, for UDS) for details on source identification and the building procedure. In brief, for both fields, sources were detected from the CANDELS mosaic in the F160W band. Total fluxes of the sources in the HST bands were measured by running SExtractor (Bertin & Arnouts 1996) in dual mode on the point-spread function (PSF)-matched images. Photometry in the lower-resolution images (e.g., ground-based and IRAC) was measured using TFIT (Laidler et al. 2007).

Redshifts used in this study include a combination of spectroscopic redshifts and photometric redshifts. Spectroscopic redshifts are used in preference if available. Photometric redshifts were computed using the official multi-wavelength photometry catalogs described above and adopting a hierarchical Bayesian approach. The typical scatter of photometric redshifts is around 0.03 to 0.06 (see Dahlen et al. 2013, for details). The best available redshifts (spectroscopic or photometric) are used as input to compute rest-frame total magnitudes from FUV to K band using EAZY (Brammer et al. 2008), which fits a set of galaxy spectral energy distribution (SED) templates to the multi-wavelength photometry. For stellar masses, we adopt the CANDELS official values released by Santini et al. (2015), which are the median of 10 separate SED fitting results (Mobasher et al. 2015) after being scaled to the Chabrier (2003) initial mass function. The typical formal uncertainty of stellar masses is \( \sim 0.1 \) dex (see Santini et al. 2015, for details).

The spatially resolved photometry is retrieved from the HST based multi-band and multi-aperture photometry catalogs of

### Table 2

Parameters of the Best Linear Fits to the Size–Mass Relations

| Redshift Range | Slope \( a \) | Zeropoint \( b \) |
|----------------|--------------|---------------|
| \( 0.5 < z < 1.0 \) | 0.155 | -0.978 |
| \( 1.0 < z < 1.4 \) | 0.133 | -0.793 |
| \( 1.4 < z < 1.8 \) | 0.116 | -0.651 |

Figure 1. Rest-frame UVJ color–color diagrams (top) for our sample galaxies after applying the selection cuts and the size–mass relations (bottom) for UVJ-defined SFGs only in three redshift bins, respectively. In the top panels, the solid lines are the classification criteria of Williams et al. (2009). SFGs are shown with solid points and color coded by \( \log R_{\text{SMA}} \). QGs are indicated by gray hatching. In the bottom panels, the solid black lines indicate the best-fit linear relations in three redshift bins, respectively. The vertical offsets from the relations (\( \Delta \log R_{\text{SMA}} \)) are used to divide our SFGs into LSFGs (\( \Delta \log R_{\text{SMA}} > 0 \)) and SSFGs (\( \Delta \log R_{\text{SMA}} < 0 \)) in each redshift bin. The gray dashed lines indicate the classification criterion of compact and non-compact SFGs in Barro et al. (2013). Data points are color coded by global ellipticity \( \epsilon_{\text{global}} = 1 - (b/a)_{\text{Galfit}} \).
CANDELS currently under construction by F. S. Liu et al. (2018, in preparation). The catalogs include the radial profiles of isophotal ellipticity ($\varepsilon$) and disky/boxy parameter $A_4$ in both F125W and F160W, and the observed surface brightness profiles in all HST/WFC3 and ACS bands if available. The detailed procedure of isophotal measurement is presented in Section 3.

Galaxy global structural parameters, which were measured by van der Wel et al. (2012) with GALFIT (Peng et al. 2002), are available for all galaxies in two fields. Imaging of each galaxy in both F125W and F160W was fitted with a single-Sérsic model, and the best-fitting Sérsic index ($n$), effective radius along the semimajor axis ($R_{SMA}$), axis ratio ($b/a$), and position angle (PA) were computed, along with estimates of their errors. We use $R_{SMA}$ as our indicator of galaxy size, rather than circularized effective radius, $R_{eff}$, because the latter depends on the axis ratio ($R_{eff} \propto \sqrt{b/a} \times R_{SMA}$), while $R_{SMA}$ is a more faithful indicator of the intrinsic size.

2.2. Sample Selection

The full GOODS-S and UDS catalogs contain 34930 (Guo et al. 2013) and 35932 (Galametz et al. 2013) objects, respectively. The parent sample used in our analysis is constructed by applying the following criteria to the catalogs:

1. Observed F160W(H) magnitude brighter than 24.5 and the GALFIT quality flag $= 0$ in F125W for $z < 1$ and F160W for $z > 1$ (van der Wel et al. 2012) to ensure well-constrained GALFIT measurements and eliminate doubles, mergers, and disturbed objects. As shown in Table 1, only about a quarter of galaxies in the combined sample of GOODS-S and UDS satisfy this criterion.

2. SExtractor Photometry quality flag PhotFlag $= 0$ to exclude spurious sources;

3. SExtractor CLASS_STAR $< 0.9$ to reduce contamination by stars;

4. Redshifts within $0.5 < z < 1.8$ and stellar masses at $9.0 < \log M_*/M_\odot < 11.0$ to maintain a high mass completeness limit for SFGs ($\sim 100\%$ at $z = 0.5$ and $\sim 85\%$ at $z = 1.8$) (van der Wel et al. 2014b) and to guarantee that all isophotal parameters can be measured in similar rest-frame optical bands.

5. Well-constrained measurements of isophotal parameters (Isophotal PhotFlag $= 0$, F. S. Liu et al. 2018, in preparation);

6. $R_{SMA} > 0' 0.18$ (3 drizzled pixels) to minimize the effect of PSF on isophotal measurements;

7. SFGs selected by rest-frame UVJ diagrams ($(U - V) < 0.88 \times (V - J) + 0.49$ for $z > 1$ and $(U - V) < 0.88 \times (V - J) + 0.59$ for $z < 1$) following the criteria defined by Williams et al. (2009);

8. Exclude a few compact SFGs (cSFGs) with the criterion of $\log \Sigma_{1.5} > 10.3$ from Barro et al. (2013), as these cSFGs might first become compact quiescent galaxies at high redshifts and later evolve into large quiescent galaxies at lower redshifts (e.g., Barro et al. 2013, 2017).

Figure 2. Distributions of global ellipticity for LSFGs (blue) and SSFGs (steel blue) in each mass-redshift bin, respectively. The median values are indicated with triangles plus dashed lines and the standard deviations ($\sigma$) are presented in the right-top corner of each panel. The galaxy numbers are presented in the left-top corner of each panel.
After the above cuts, we obtain 4595 SFGs: 2033 from GOODS-S and 2562 from UDS. Table 1 lists the resulting sample size after each selection criterion has subsequently been applied. The top panels of Figure 1 present the rest-frame UVJ diagrams for our galaxies in three redshift bins. SFGs defined by the criteria of Williams et al. (2009) are shown with blue dots and color coded by R \text{log SMA}. Quiescent galaxies are excluded in this work and they are located in the gray hatched upper corners of the diagrams. The bottom panels of Figure 1 show the size–mass relations for UVJ-defined SFGs only in the three adopted redshift bins. The size–mass panels are color coded by the global ellipticity defined as ε_{global} = 1 - (b/a)_{Galfit}. To derive the mean size–mass relations, an initial fit to all SFGs is made, then objects more than 2σ away from the fit are excluded. This fitting process is repeated iteratively until no new objects are excluded. The parameters of the final fits are presented in Table 2. The solid black lines in the bottom panels of Figure 1 indicate the adopted best-fit linear relations to the galaxies. After the fits are done, vertical offsets from the relations are calculated for our SFGs in each bin. The offset for a given galaxy is denoted by Δ log R_{SMA}. For simplicity, we hereafter refer to galaxies, in a given mass and redshift bin, with Δ log R_{SMA} > 0 (i.e., larger than average) as Large SFGs (LSFGs), and galaxies with Δ log R_{SMA} < 0 as Small SFGs (SSFGs). It should be pointed out that our slopes are systematically shallower by ~0.1 dex compared to the fits by van der Wel et al. (2014b), likely due to the exclusion of very small galaxies with R_{SMA} < 0.18. These small discrepancies do not affect our results, as we are only concerned with relative size differences at fixed mass and redshift.

To study evolutionary trends as a function of redshift and mass more easily, we divide the sample into four mass bins (9.0 < log M_⋆ < 9.5, 9.5 ≤ log M_⋆ < 10.0, 10.0 ≤ log M_⋆ < 10.5 and 10.5 ≤ log M_⋆ < 11.0) and three redshift bins (0.5 < z < 1.0, 1.0 < z < 1.4, and 1.4 < z < 1.8). This grid diagram is a powerful visualization tool to track the movement of galaxies as they evolve in mass with time. Figure 2 shows the distributions of ε_{global} and corresponding median values (ε_{global,med}) for SSFGs and LSFGs in each mass-redshift bin, respectively. In order to clearly recognize the intrinsic structure of galaxies, we further divide our sample galaxies in each bin...
into two sub-classes: “edge-on” ($\varepsilon_{\text{global}} > \varepsilon_{\text{global,med}}$) and “face-on” ($\varepsilon_{\text{global}} < \varepsilon_{\text{global,med}}$), according to the relative “inclination.” To guarantee that our isophotal analysis is done in similar rest-frame optical bands, we measure the isophotal profiles in F160W band for $z > 1$ galaxies and in F125W band for $z < 1$ galaxies.

### 3. Measurement of Isophotal Shape Profiles

The radial profiles of galaxy isophotal parameters ($\varepsilon$ and $A_4$) used in this work come from the HST based multi-wavelength and multi-aperture photometry catalogs built by F. S. Liu et al. (2018, in preparation). The isophotal parameters are measured by using the IRAF routine ellipse within STSDAS, which is based on a technique described by Jedrzejewski (1987).

Before continuing, we summarize the measurement process as below.

First, we trimmed the original PSF-matched mosaic images in each band to generate multi-band cut-out images centered on a target galaxy. Before the ellipse fitting, SExtractor was used to identify sources within the detection limit and remove them to obtain a background-only image for each band. We then applied the median filter to build a local background image in each band, using sigma clipping to reduce the impact of relatively brighter residual background sources. This local background was then subtracted from each cut-out image. We verified that the flux distributions in empty regions of each cut-out image in each band are centered on zero after the background subtraction.

After background subtraction, we run SExtractor again on the trimmed image to generate a “SEGMENTATION” image, which identifies all objects with flags in the image. A mask image, with all of the detected objects flagged except the galaxy of interest, can then be obtained from the “SEGMENTATION” image. We carefully examined all of the mask images in each band and corrected a few bad images manually to create good mask images for all galaxies. Photometry was then performed on the trimmed images with the masked areas excluded from the reduction.

We use the geometric center, ellipticity, PA, and effective radius along the semimajor axis of sample galaxies obtained from the GALFIT measurements by van der Wel et al. (2012) as initial values in the ellipse fitting. In the ellipse task, the image intensity is first sampled along a trial ellipse generated using these parameters, and the intensity string $I(\theta)$ is

![Figure 4](image-url)

**Figure 4.** Example nearly face-on galaxies GOODS-S 10421, GOODS-S 26255, and UDS 12524 illustrating the measurement of isophotal shape profile. The data points, error-bars and lines have the same meanings as those in Figure 3.
expanded in a Fourier series, 

\[ I(\theta) = I_0 + \sum_{n=1}^{N} [A_n \cos(n\theta) + B_n \sin(n\theta)] \]  

(1)

where \( I(\theta) \) is the intensity (in units of ADU s\(^{-1}\) pixel\(^{-1}\)) on the ellipse in the direction of \( \theta \), \( I_0 \) is the average intensity of the ellipse, the PA \( \theta \) is defined to be 0° along the positive y-axis and increases counter clockwise. \( N \) is the highest harmonic fitted, \( A_n \) and \( B_n \) are the Fourier coefficients. The most significant non-zero component of the Fourier analysis is the \( A_4 \) parameter (corresponding to the cos(4\( \theta \)) term). Using the sign of this parameter, the isophote of a galaxy can be classified into disky (\( A_4 > 0 \)) and boxy (\( A_4 < 0 \)).

During the fitting, we allow the geometric center, ellipticity and PA to vary freely. Successive ellipses are fitted along the major axis, starting from the effective radius and moving inward and outward with a logarithmic step of 0.3, until the ellipse fitting process fails to converge. The output of the ellipse is a table containing the radial profiles of many isophotal parameters along with their uncertainties, such as ellipticity (\( \varepsilon \)), Fourier coefficients (i.e., \( A_4 \)), PA, and surface brightness in each elliptic annulus. Figures 3 and 4 illustrate our measurements with three nearly edge-on galaxies (GOODS-S 14994, GOODS-S 22208 and GOODS-S 19762) and three nearly face-on galaxies (GOODS-S 10421, GOODS-S 26255 and UDS12524) in three different redshift bins.

We stress that two important steps in the above process are the local background subtraction and the use of a large logarithmic step, which can significantly improve the accuracy of the measurements. More technical details about the measurements will be included in the future documentation of the F. S. Liu et al. (2018, in preparation) catalogs.

4. Result and Analysis

To derive the stacked \( \varepsilon \) and \( A_4 \) profiles for each sub-class in every mass-redshift bin, we utilized IRAF/proto to perform cubic spline interpolation and then computed the median value and 68% distribution of the scatter for every selected position in each bin. The resulting median \( \varepsilon \) and \( A_4 \) as a function of normalized radius (\( R = R/R_{\text{SMA}} \)) for SSFGs and LSFGs are shown in Figures 5–8, respectively. Note that not every galaxy has a reliable measurement of isophotal profile that extends to large radius. The median values at the positions where the
| Stellar Mass | Sub-class | 1.4 < z < 1.8 | 1.0 < z < 1.4 | 0.5 < z < 1.0 |
|--------------|-----------|----------------|----------------|----------------|
|              | Slope     | Intercept      | R-squared      | Break $R^2$    | Slope     | Intercept      | R-squared      | Break $R^2$    | Slope     | Intercept      | R-squared      | Break $R^2$    |
| 9.0 < log $M_*$ < 9.5 | face-on   | 0.033 ± 0.098 | 0.252 ± 0.011 | 0.59 ± 1.06    | 0.184 ± 0.133 | 0.275 ± 0.027 | 0.60 ± 0.80 | 0.070 ± 0.014 | 0.227 ± 0.002 | 0.92 ± 1.26 |
|              |           | −0.033 ± 0.016 | 0.254 ± 0.017 | ...            | −0.039 ± 0.023 | 0.253 ± 0.031 | ...            | −0.057 ± 0.014 | 0.240 ± 0.002 | ...            |
|              |           | 0.085 ± 0.052 | 0.414 ± 0.005 | 0.87 ± 1.12    | 0.141 ± 0.017 | 0.398 ± 0.003 | 0.98 ± 1.03 | 0.160 ± 0.363 | 0.433 ± 0.006 | 0.91 ± 0.96 |
|              |           | −0.101 ± 0.031 | 0.424 ± 0.007 | ...            | −0.037 ± 0.007 | 0.400 ± 0.003 | ...            | −0.045 ± 0.015 | 0.432 ± 0.003 | ...            |
| 9.5 < log $M_*$ < 10.0 | face-on   | −0.075 ± 0.021 | 0.216 ± 0.005 | 0.69 ± ...      | 0.065 ± 0.029 | 0.581 ± 0.007 | 0.86 ± 0.96 | 0.025 ± 0.012 | 0.168 ± 0.002 | 0.64 ± 1.00 |
|              |           | ...            | ...            | ...            | −0.085 ± 0.018 | 0.208 ± 0.009 | ...            | −0.055 ± 0.026 | 0.184 ± 0.001 | ...            |
|              |           | 0.080 ± 0.018 | 0.377 ± 0.002 | 0.96 ± 1.25    | 0.121 ± 0.019 | 0.395 ± 0.003 | 0.92 ± 1.18 | 0.164 ± 0.353 | 0.399 ± 0.006 | 0.87 ± 1.51 |
|              |           | −0.149 ± 0.017 | 0.400 ± 0.002 | ...            | −0.091 ± 0.025 | 0.411 ± 0.003 | ...            | −0.287 ± 0.089 | 0.480 ± 0.004 | ...            |
| 10.0 < log $M_*$ < 10.5 | face-on   | −0.029 ± 0.022 | 0.157 ± 0.003 | 0.71 ± 1.67    | 0.110 ± 0.053 | 0.188 ± 0.014 | 0.62 ± 0.73 | 0.137 ± 0.012 | 0.176 ± 0.003 | 0.97 ± 1.57 |
|              |           | 0.196 ± 0.147 | 0.107 ± 0.003 | ...            | −0.019 ± 0.013 | 0.170 ± 0.012 | ...            | −0.147 ± 0.050 | 0.232 ± 0.002 | ...            |
|              |           | −0.032 ± 0.028 | 0.351 ± 0.004 | 0.92 ± 1.66    | 0.234 ± 0.043 | 0.344 ± 0.010 | 0.97 ± 1.01 | 0.265 ± 0.012 | 0.405 ± 0.003 | 0.99 ± 1.61 |
| 10.5 < log $M_*$ < 11.0 | face-on   | −0.252 ± 0.056 | 0.399 ± 0.004 | ...            | 0.063 ± 0.029 | 0.344 ± 0.009 | ...            | −0.255 ± 0.045 | 0.513 ± 0.001 | ...            |
|              |           | 0.250 ± 0.201 | 0.260 ± 0.080 | 0.64 ± 0.51    | 0.216 ± 0.043 | 0.169 ± 0.011 | 0.93 ± 0.94 | 0.144 ± 0.024 | 0.198 ± 0.009 | 0.92 ± 1.26 |
|              |           | 0.016 ± 0.024 | 0.192 ± 0.043 | ...            | −0.003 ± 0.040 | 0.163 ± 0.015 | ...            | 0.048 ± 0.088 | 0.208 ± 0.009 | ...            |
|              |           | 0.305 ± 0.020 | 0.373 ± 0.005 | 0.99 ± 1.58    | 0.300 ± 0.012 | 0.343 ± 0.002 | 0.99 ± 1.89 | 0.346 ± 0.015 | 0.379 ± 0.004 | 0.99 ± 1.83 |
|              |           | −0.308 ± 0.074 | 0.495 ± 0.003 | ...            | −0.318 ± 0.097 | 0.514 ± 0.002 | ...            | −0.316 ± 0.205 | 0.553 ± 0.006 | ...            |

**Table 3**

Best-fit Parameters for the Ellipticity and $A_*$ Profiles
Table 3
(Continued)

Best-fit parameters for the $A_4$ profiles of LSFGs (Figure 8)

| Stellar Mass   | Sub-class | 1.4 < z < 1.8 | 1.0 < z < 1.4 | 0.5 < z < 1.0 |
|---------------|-----------|---------------|---------------|---------------|
|               |           | Slope         | Intercept     | $R^2$         | Slope         | Intercept     | $R^2$         | Slope         | Intercept     | $R^2$         |
| edge-on       |           | 0.250 ± 0.010 | 0.517 ± 0.002 | 0.99 1.85    | 0.262 ± 0.016 | 0.520 ± 0.003 | 0.98 1.73     | 0.422 ± 0.016 | 0.567 ± 0.005 | 0.99 1.50     |
|               |           | 0.598 ± 0.127 | 0.744 ± 0.001 | ...          | −0.812 ± 0.154 | 0.776 ± 0.003 | ...           | −0.562 ± 0.088 | 0.739 ± 0.005 | ...           |

Note. 
$^a R = R_{R_{SMA}}$. 
fractions of accurate data points are below $1\sigma$ are removed in our analysis.

To quantify the general trends of composite $\varepsilon$ and $A_4$ profiles in each mass-redshift bin, we used the segmented package in R programming language to fit two broken lines model to each profile outside the PSF FWHM (0.9 18). The model is estimated simultaneously yielding point estimates and relevant approximate standard errors of all the model parameters, including the break-point where the linear relation changes. If the two broken lines model fails to fit a profile, the program automatically generates a single linear regression model. The best-fit parameters are given in Table 3, including the slopes, intercepts, relevant standard errors, break-radii, and $R$-squared values. The $R$-squared value quantifies how well the model fits the data. A $R$-squared value close to one indicates a perfect fit and a $R$-squared value close to zero indicates a bad fit. It can be seen from Table 3 that the majority of the segmented models have the slope values within ±0.2 of zero in both face-on and edge-on views, especially at $z > 1$ (Figure 5). The average ellipticity values are $\sim$0.4 for edge-on and $\sim$0.2 for face-on, which shows that these systems are not highly flattened intrinsically. The flat $\varepsilon$ profiles in face-on views are generally consistent with our expectations and therefore are not surprising. On the contrary, if these galaxies harbor disks and are viewed edge-on, a significant change in $\varepsilon$ with increasing radius should be observed (Zheng et al. 2015). However, such a trend is not observed in edge-on views. These findings indicate that these galaxies are likely composed of a single component and are not disk-like. In addition, we find that the SSFGs in these bins also have nearly flat $A_4$ profiles (the slopes of segmented models are within ±0.02 of zero) in both face-on and edge-on views; moreover, the median values of $A_4$ at all radii are almost zero. The findings imply that statistically these galaxies are not rotationally supported and thus they do not likely have disks. These systems may not be spheroidal either, because these galaxies usually have Sérsic indices $n \sim 1$ (Wuyts et al. 2011). Hao et al. (2006) showed the relation between $\varepsilon$ and $A_4$ for nearby massive spheroids, which indicates that a spheroidal system with $\varepsilon = 0.4$ is usually disky ($A_4 > 0$). If this relation still holds for low-mass systems at higher redshifts, it would again support that these galaxies may not be spheroids. Furthermore, it can be seen in Figure 6 that the $A_4$ points of these galaxies distribute on both sides of the
A_4 = 0 lines randomly, and the face-on and edge-on systems are mixed together. The findings suggest that these galaxies are likely to have irregular structures without distinct boundaries of components.

Likewise, the low-mass \((M_\odot < 10^{10}M_\odot)\) LSFGs \((\Delta \log R_{\text{SMA}} > 0)\) in the same bins also have relatively flat \(\varepsilon\) profiles in face-on views (Figure 7). However, when seen in edge-on, these large systems have \(\varepsilon\) profiles that mainly increase monotonically with radius (the slopes of inner line models are larger than \(\sim 0.2\)). We note that, although some LSFGs have decreasing \(\varepsilon\) profiles in their outermost regions, these trends are relatively weak compared to those observed in high-mass galaxies.

For the low-mass LSFGs, the average ellipticity values are \(\sim 0.55\) for edge-on views and \(\sim 0.35\) for face-on views, which implies that these systems are more flattened intrinsically than the SSFGs in the same mass-redshift bins. We further show that the low-mass LSFGs exhibit positive \(A_4\) (disky) profiles that dominate in the intermediate regions, when seen in edge-on compared to face-on views (Figure 8). This feature implies that these large galaxies likely harbour disk-like components flattened by rotation.

2. At high masses \((M_\odot > 10^{10}M_\odot)\), the SSFGs also have nearly flat \(\varepsilon\) profiles in face-on views (Figure 5). However, in edge-on views, the \(\varepsilon\) profiles of SSFGs exhibit a distinct feature compared to low-mass SSFGs: a first significant increase with radius in the inner regions \((\text{slopes of inner line models are larger than } 0.2)\), going through a maximum, then a decrease in the outskirts \((\text{slopes of outer line models become negative})\), which is more prevalent for more massive \((M_\odot > 10^{10.5}M_\odot)\) galaxies or at lower redshifts \((z < 1.4)\). Such a feature is more remarkable for the LSFGs (see Figure 7). Even in a face-on view, a similar feature can be seen in the most massive \((M_\odot > 10^{10.5}M_\odot)\) LSFGs. This feature is likely formed due to the co-existence of multiple components: bulges in the inner regions, disks in the intermediate regions, and halo-like stellar components in the outskirts. When the galaxy is highly inclined (edge-on) and the ellipticity profile can tell us the relative flattening of various components, the central bulge and outer stellar halo look much rounder than the disk in the intermediate region. In addition, one can also find similar features in the corresponding \(A_4\) profiles of edge-on systems (Figures 6 and 8): the isophotes in the intermediate regions are obviously disky, whereas the inner and outer isophotes are close to perfect ellipses \((A_4 \sim 0)\). Furthermore, compared to the low-mass \((M_\odot < 10^{10}M_\odot)\) galaxies.

Figure 7. The composite ellipticity profiles as a function of normalized radius for the LSFGs in classified mass-redshift bins. The blue diamonds with red edge represent the median values of ellipticities at every given radius for edge-on systems, followed by 68% confidence intervals. The blue circles with green edges represent the median values of ellipticities at every given radius for face-on systems, followed by 68% confidence intervals. The shaded regions indicate the ranges affected significantly by PSF smoothing \((0''/18)\). The galaxy number of each class is shown on the right-top corner of each panel. The thick black arrows indicate the position of \(R_{\text{SMA}} = 1.5\text{kpc}\) in each bin. The observed data are shown with tiny dots for edge-on (red) and face-on (green) systems, respectively. The shaded regions show the best segmented models with \(2\sigma\) lower and upper limits for edge-on (red) and face-on (green) systems.
at the same redshifts, the intermediate regions of high-mass galaxies are more disky (with larger $A_4$ values) in edge-on views. This implies that these massive galaxies likely harbour disks with faster rotation.

Additionally, in order to clearly trace the variation of ellipticities in the inner regions as galaxies evolve in mass with time, in Figure 9 we present the distributions of ellipticity at $R = 1.5$ kpc ($e_{1.5}$) for the SSFGs and LSFGs in each mass-redshift bin, respectively. This physical position is relatively close to the centers of galaxies but the ellipticity measurement at this position is less affected by PSF smoothing compared to the very center within $R_{SMA} < 0.18$, as indicated in Figures 5 and 7. It can be seen that, as galaxies evolve toward the high stellar masses and low redshifts, statistically the $e_{1.5}$ of both SSFGs and LSSFGs tend to decrease (become rounder).

To double-check our results, we visually inspect the images of sample galaxies carefully. In Figure 10, we present four example cut-out images of highly inclined systems for different mass-redshift bins. In each panel, the upper two images are for LSFGs and the lower two are for SSFGs. Obviously, in the low-mass ($M_* < 10^{10} M_\odot$) and high-redshift ($z > 1$) bins, the images of SSFGs exhibit good consistency with no obvious disk-like feature (mostly irregular morphology). In contrast, the images of LSFGs in the same bins indeed exhibit somewhat disk-like structure. As galaxies evolve toward the high masses ($M_* \approx 10^{10} M_\odot$) and low redshifts ($z < \sim 1.4$), the disk feature becomes more prominent in both LSFGs and SSFGs. In the meanwhile, the diffuse halo-like stellar components appear to dominate the outer regions of galaxies. The visual inspection is in good agreement with our quantitative analysis of the isophotal structure.

5. Discussion and Summary

We have measured the radial profiles of isophotal ellipticity ($\varepsilon$) and $A_4$ out to radii of $\sim 3R_{SMA}$ in similar rest-frame optical band for ~4600 SFGs between redshift 0.5 and 1.8 in the Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey/GOODS-S and UDS fields. With this sample, we study the stacked $\varepsilon$ and $A_4$ profiles on an evolutionary grid laid out by stellar mass and redshift (see Figure 6 in Fang et al. 2017). The grid system is a powerful visualization tool to track the movement of galaxies as they evolve along stellar mass growth tracks based on estimates of how galaxies grow in mass with time (Moster et al. 2013; Papovich et al. 2015). For the first time, we make a statistically robust analysis of the isophotal structure of distant SFGs. Based on their relative distances from the mean size–mass relation in a given redshift bin, we divide our galaxies into relatively SSFGs and LSFGs. We find that statistically these two classes exhibit different structure of the isophotal shape. Our main conclusions are as follows:
1. At low masses ($M_\star < 10^{10}M_\odot$), the SSFGs generally have nearly flat $\epsilon$ and $A_4$ profiles in both edge-on and face-on views especially at $z > 1$. Moreover, the median $A_4$ values at all radii are almost zero but the $A_4$ distributions have quite large scatters. In contrast, the highly inclined (nearly edge-on) LSFGs in the same mass-redshift bins generally have $\epsilon$ profiles that mainly increase monotonically with radius and disky profiles ($A_4 > 0$) that dominate in the intermediate regions. The findings imply that these SSFGs are not disk-like, whereas the LSFGs likely harbour disk-like components flattened by significant rotation.

2. At high masses ($M_\star > 10^{10}M_\odot$), both highly inclined SSFGs and LSFGs generally exhibit distinct $\epsilon$ and $A_4$ profiles features that first increase with radius, reach maxima, and then decrease. Such feature is more prevalent at lower redshifts ($z < 1.4$) or for more massive ($M_\star > 10^{10.5}M_\odot$) galaxies. This feature can be likely formed due to the co-existence of central bulges, disks in the intermediate regions and halo-like stellar components in the outskirts. In addition, compared to the low-mass SFGs at the same redshifts, the intermediate isophotes in the highly inclined massive SFGs are more disky, which indicates that these massive galaxies likely harbour disks with faster rotation.

3. Central ellipticities of both SSFGs and LSFGs tend to decrease with increasing mass and decreasing redshift (become rounder). Moreover, the peak values of both ellipticity and $A_4$ tend to increase as galaxies increase in mass with time. These findings likely indicate that the bulges build up in lockstep with disk growth.

Recently, van der Wel et al. (2014a) constructed the intrinsic, three-dimensional distributions of global axis ratio ($b/a = 1 - \epsilon$) of distant SFGs through the projected images. They showed that the low-mass ($M_\star < 10^{10}M_\odot$) SFGs with $z > 1$ possess a broad range of geometric shapes, and the fraction of non-disk (probably prolate) galaxies increases at higher redshifts and lower masses. This is generally consistent with our finding. More recently, Liu et al. (2016) showed that the rest-frame NUV$-B$ color gradients in the low-mass ($M_\star < 10^{10}M_\odot$) SFGs at $z \sim 1$ are generally flat after correcting for dust reddening, which implies that the newly formed stars in these galaxies may be randomly mixed with previously existing population. These galaxies may be supported dominantly by random motions. Liu et al. (2016)’s result is also in agreement with our $A_4$ analysis. Recent cosmological hydrodynamical zoom-in simulation by Ceverino et al. (2014) shows that low-mass galaxies at high redshifts can be an elongated, bar-like systems with irregular morphology. The large and homogeneous survey with integral field spectroscopy by KMOS (e.g., Wisnioski et al. 2015) reveals that $\sim$83% of SFGs with $M_\star = 3 \times 10^9 - 7 \times 10^{11}M_\odot$ at
0.7 < z < 2.7 are rotation dominated and ~70% of SFGs are disk-like systems. Galaxies that are resolved by KMOS but not rotating are found primarily at low stellar masses. These findings are also generally consistent with our isophotal analysis.

We caution that it is not clear whether the change in the ellipticity is observed for single-component rotating disks. In addition, the relation between positive $A_4$ and fast rotation is known in nearby early-type galaxies (e.g., Hao et al. 2006) only. Thus, it is also not clear whether single-component disk galaxies tend to have positive $A_4$ values. We interpret the increasing inner and decreasing outer profiles of ellipticity and $A_4$ as the consequence of the multiple components of bulges, disks, and stellar halos. However, it has been known that SFGs often harbor additional substructures such as spiral arms, rings, clumps, and bars (e.g., Erwin & Sparke 2002; Cheung et al. 2013; Guo et al. 2015). The spiral arms, clumps, and rings tend to appear randomly and they may not affect our profiles once they are stacked, whereas bars could have effect on our results (e.g., Erwin & Debattista 2013).

We show the distributions of Sérsic index ($n$) of our sample galaxies in the same mass-redshift grid in Figure 11. It can be seen that both LSFGs and SSFGs tend to increase their Sérsic index as galaxies evolve toward the high masses and low redshifts. This indicates that the fraction of bulge-dominated systems likely increases as galaxies evolve. This is in agreement with many previous studies (e.g., van der Wel et al. 2011; Bruce et al. 2012; Huertas-Company et al. 2015; Margalef-Bentabol et al. 2016; Barro et al. 2017). It should be noted that Sérsic indices here are not the bulge Sérsic indices but the total ones. A more careful investigation on bulge Sérsic indices by using bulge+disk decomposition technique is needed in the near future.

What leads the ellipticities in the outskirts of the highly inclined massive galaxies to decrease significantly is quite interesting. Based on our isophotal analysis and visual inspection on images, we propose an interpretation with the contribution of a halo-like stellar component in the outer region. Zheng et al. (2015) showed that the composite ellipticity profile of nearby disk galaxies rises slowly between

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**Figure 10.** Cut-out images of example edge-on galaxies in F160W (for 1.0 < z < 1.8) and F125W (for 0.5 < z < 1.0) in every mass-redshift bin. The size of each cut-out image is 50 x 50 kpc. The cyan ellipse in each cut-out image indicates the outermost isophote we measured, which is close to the position of ~3R_SMA. The red ellipses indicate the positions of maximum ellipticity in the ε profiles of some galaxies with diffuse halo-like stellar components. In each bin, the upper images are for LSGFs, whereas the lower ones are for SSFGs.
\( R_{0.5} \) and \( R_{1.4} \) and then slowly declines out to \( R_{3.0} \) (see Figure 11 in their paper). Note that, for a pure disk galaxy having an exponential radial surface brightness profile, \( R_{90} \) is roughly twice the effective radius. The transition radii in the ellipticity profiles of our massive SFGs are roughly between \( R_{SMA} \) and \( 2R_{SMA} \), which are slightly smaller but already comparable to that of nearby disk galaxies reported by Zheng et al. (2015). In addition, we showed that the outer ellipticity and A4 beyond \( 2R_{SMA} \), seem to be constant, which might favor the scenario that the halo-like stellar components already exist at high redshifts (i.e., \( z \sim 2 \)). We caution that it is possible that the cosmological surface brightness dimming makes it difficult to observe faint stellar halos at high redshifts. Zheng et al. (2015) further showed that the characteristic radial profiles of color, stellar mass-to-luminosity ratio, and stellar age of nearby disk galaxies have a “U” shape (they first decline with increasing radius, but then rise in the outer region). The minima are also located at radii of around 0.8–1.0\( R_{90} \) or at locations where the local stellar mass surface density is \( \sim 10 M_\odot/\text{pc}^2 \). These findings further support the contribution of the halo light beyond this radius. With these observational results, Zheng et al. (2015) argued that a combination of a radial migration of stars in the inner region and a truncation of recent star formation in the outer part is likely to be required to regulate the evolution of disk galaxies. The general trend for nearby disk galaxies to have redder (older) outer disks and stellar halos has also been reported by other works (e.g., Bakos et al. 2008; Yoachim et al. 2010, 2012; Bakos & Trujillo 2012; González Delgado et al. 2014). To better comprehend the formation of stellar halos in local SFGs, it will be especially helpful to further study the spatial distributions of stellar mass and other stellar population properties of their progenitors. We will perform a thorough investigation of the stellar population distribution for a subsample of massive SFGs with distinct halo-like stellar components at moderate redshift in a follow-up work.

We acknowledge the anonymous referee for a constructive report that significantly improved this paper. This project was supported by the NSF grants of China No.11573017 and 11733006. We acknowledge the support of the CANDELS program HST-GO-12060 by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NAS5-26555. S.M.F., Y.G., D.C.K., and H.M.Y. acknowledge partial support from US NSF grant AST-16-15730. X.Z.Z. thanks support from the National Key Research and Development Program of China (No. 2017YFA0402703), NSFC (grant 11773076) and the Chinese Academy of Sciences (CAS) through a grant to the

![Figure 11. Distributions of Sérsic Index n for the LSFGs (blue) and SSFGs (steel blue) in every mass-redshift bin, respectively. The median values are indicated with triangles plus dashed lines and the standard deviations (\( \sigma \)) are presented in the right-top corner of each panel.](image-url)
