Edge-on Galaxies in the Hubble Ultra Deep Field

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Abstract—We have produced a sample of 58 edge-on spiral galaxies at redshifts $z \sim 1$ selected in the Hubble Ultra Deep Field. For all galaxies we have analyzed the 2D brightness distributions in the $V_{606}$ and $i_{775}$ filters and measured the radial ($h_r$) and vertical ($h_z$) exponential scale lengths of the brightness distribution. We have obtained evidence that the relative thickness of the disks of distant galaxies, i.e., the ratio of the vertical and radial scale lengths, on average, exceeds the relative thickness of the disks of nearby spiral galaxies. The vertical scale length $h_z$ of the stellar disks of galaxies shows no big changes at $z \lesssim 1$. The possibility of the evolution of the radial scale length $h_r$ for the brightness distribution with redshift is discussed.

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INTRODUCTION

A study of edge-on spiral galaxies allows a number of important problems of extragalactic astronomy to be investigated: the structure and stability of galactic disks, the properties and distribution of dust in them, the contribution of dark matter to the structure of galaxies, the large-scale distribution of galaxies, etc. (see, e.g., van der Kriut and Searl 1981; Zasov et al. 1991; de Grijs 1998; Mosenkov et al. 2010, 2016; Bizyaev et al. 2017; Makarov et al. 2018; and references therein). The preceding papers were devoted mostly to edge-on galaxies in the nearby Universe. Only in a few papers was the vertical structure of distant objects studied. For example, Reshetnikov et al. (2003) investigated edge-on galaxies in the northern and southern Hubble Deep Fields. They found that the relative thickness of the stellar disks of galaxies at redshifts $z \sim 1$ exceeds the relative thickness of the disks of nearby galaxies by a factor of 1.5–2. This conclusion was confirmed when analyzing the structure of galaxies in the Hubble Ultra Deep Field (hereafter HUDF) (Elmegreen et al. 2005; B. Elmegreen and D. Elmegreen 2006).

The goal of our paper is a photometric study of edge-on spiral galaxies in the HUDF. The main differences between our paper and the previously published studies are: an analysis of the complete two-dimensional (2D) brightness distributions instead of the one-dimensional profiles, using the spectroscopic redshifts for most objects, and a larger size of the sample of edge-on galaxies.

All of the numerical values in our paper are given for the cosmological model with a Hubble constant of 70 km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$.

THE SAMPLE OF GALAXIES AND DATA REDUCTION

To study the edge-on spiral galaxies, we used the HUDF frames in the F606W (hereafter $V_{606}$) and F775W ($i_{775}$) filters (Beckwith et al. 2006). In these color bands the HUDF images are deeper than those in other original filters. The pixel size is 0.03″.

In the first step, on the field image in the $V_{606}$ filter we selected 901 galaxies with an apparent flaring $b/a \leq 0.55$, an area $\geq 24$ pixels, and S/N $> 3$ in each pixel using the SExtractor package (Bertin and Arnouts 1996). Such a significant constraint on the flattening was used in order not to throw away the galaxies with close neighbors. In several cases, SExtractor does not separate them, but detects them as a single object. Next, based on a visual examination of the images for the objects in different filters and with different brightness contrasts, we left 77 candidates for edge-on galaxies in the sample.

To analyze the photometric structure (decomposition) of the galaxies, we used the Imfit package (Erwin 2015) with the PSF (point spread function)
Fig. 1. Examples of photometric modeling for three sample galaxies. From left to right: the original image, the model, and the difference of the original and model images. The upper, middle, and lower rows show, respectively, the images of galaxies 9 (the frame size along the horizontal axis is 4.6″), 22 (the corresponding size is 3.8″), and 27 (4.6″) from Table 1.

generated for the HUDF by the Tiny Tim code (Krist et al. 2011). A comparison of the PSF with the sample objects showed that the disks of all galaxies are resolved with confidence in both radial and vertical directions.

In the selected candidates for edge-on galaxies the bulges are noticeable approximately in a quarter of the objects. In most cases, these bulges are faint and are on the verge of resolution. Therefore, to describe the photometric structure of the galaxies, we chose the simplest model of an edge-on double exponential disk (see, e.g., van der Kruit and Searl 1981):

$$I(r, z) = I_{0, 0} \left( \frac{r}{h_r} \right) K_1 \left( \frac{r}{h_r} \right) e^{-z/h_z},$$

where $I_{0, 0}$, $h_r$, and $h_z$ are the central surface brightness, radial and vertical exponential scale lengths of the disk, respectively, and $K_1$ is a modified first-order Bessel function. The bulges, if they were visible, were fitted by a Sérsic function. The nearby objects projected onto the galaxies under study were masked before the Imfit operation. If, however, the area of the hampering objects was too large, then during the decomposition they were fitted by a combination of different model functions and were subtracted.

An analysis of the difference images (the original image minus the model one) revealed that 19 of the 77 galaxies either are not edge-on galaxies or have a very complex and asymmetric structure. These objects were excluded from the subsequent consideration. Thus, the final sample of edge-on galaxies studied in our paper consists of 58 objects. Examples of our photometric analysis for three galaxies are given in Fig. 1.

For 33 sample galaxies we took their spectroscopic redshifts from Inami et al. (2017) and Rafelski et al. (2015). For 23 objects we used the photometric redshifts from Rafelski et al. (2015) (BPZ redshifts). For two galaxies the redshifts were not found.

The final characteristics of the candidates for edge-on galaxies in the HUDF are listed in Table 1. Column 1 in Table 1 gives the object ordinal number in the sample, columns 2 and 3 provide the coordinates of the galactic center on the original HUDF image in pixels, the next columns give the galaxy number from Coe et al. (2006) and its apparent magnitude.
Table 1. Edge-on galaxies in the HUDF

| No. | X     | Y     | CoeID | $V_{606}$ | $z$   | eon | Fit | $h_r$, kpc | $h_z$, kpc |
|-----|-------|-------|-------|-----------|------|-----|-----|------------|------------|
| 1   | 1488  | 4578  | 6870  | 27.05     | 1.14 | 1   | 3   | 0.21"     | 0.21"     | 0.03"     | 0.03"     |
| 2   | 1744  | 6169  | 5234  | 26.48     | 2.02; | 3   | 1   | 1.76       | 1.48       | 0.40       | 0.44       |
| 3   | 1941  | 4739  | 3840  | 26.77     | 0.59; | 3   | 1   | 1.40       | 1.20       | 0.37       | 0.37       |
| 5   | 2084  | 4477  | 3299  | 25.51     | 1.22  | 2   | 2   | 2.11       | 1.92       | 0.46       | 0.49       |
| 6   | 2148  | 6006  | 6478  | 25.81     | 2.94; | 2   | 2   | 2.51       | 2.42       | 0.60       | 0.57       |
| 7   | 2697  | 6387  | 7022  | 25.03     | 1.55  | 3   | 3   | 2.79       | 2.50       | 0.81       | 0.77       |
| 8   | 2701  | 5920  | 6278  | 26.62     | 0.94  | 2   | 2   | 2.77       | 2.47       | 0.41       | 0.42       |
| 9   | 2738  | 4401  | 3315  | 27.58     | 0.97; | 2   | 1   | 1.99       | 1.75       | 0.31       | 0.34       |
| 10  | 3240  | 3843  | 2332  | 26.29     | 0.52  | 3   | 2   | 1.18       | 1.08       | 0.39       | 0.41       |
| 11  | 3401  | 2811  | 1057  | 24.83     | 0.74; | 1   | 2   | 3.66       | 3.28       | 0.55       | 0.59       |
| 12  | 3631  | 5784  | 5995  | 25.04     | 0.95  | 3   | 2   | 1.22       | 1.20       | 0.52       | 0.52       |
| 13  | 3973  | 6512  | 7269  | 24.23     | 0.73  | 1   | 2   | 3.50       | 3.51       | 0.70       | 0.74       |
| 14  | 4140  | 6814  | 8801  | 25.78     | 1.31  | 3   | 1   | 2.37       | 2.35       | 0.57       | 0.60       |
| 15  | 4168  | 6469  |       |          |       |     | 3   | 1   | 0.18"     | 0.16"     | 0.05"     | 0.04"     |
| 16  | 4186  | 4249  | 3097  | 26.56     | 2.36; | 3   | 1   | 1.67       | 1.59       | 0.63       | 0.59       |
| 17  | 4213  | 3054  | 1242  | 26.34     | 2.02; | 2   | 2   | 4.04       | 3.72       | 0.69       | 0.68       |
| 18  | 4312  | 8261  | 9414  | 27.25     | 1.38; | 3   | 1   | 1.96       | 1.66       | 0.44       | 0.46       |
| 19  | 4362  | 1468  | 163   | 27.43     | 0.65; | 3   | 1   | 1.09       | 1.07       | 0.22       | 0.23       |
| 20  | 4462  | 2075  | 521   | 25.93     | 1.04; | 1   | 2   | 2.53       | 2.53       | 0.48       | 0.51       |
| 21  | 4673  | 7460  | 8259  | 27.33     | 0.68  | 3   | 1   | 1.17       | 1.12       | 0.31       | 0.31       |
| 22  | 4675  | 5841  | 6143  | 26.97     | 1.02  | 1   | 1   | 1.67       | 1.45       | 0.33       | 0.38       |
| 23  | 4780  | 1333  | 95    | 26.21     | 1.76; | 2   | 2   | 1.64       | 1.56       | 0.43       | 0.45       |
| 24  | 4853  | 4000  | 2652  | 25.17     | 0.68  | 1   | 2   | 2.46       | 2.40       | 0.46       | 0.47       |
| 25  | 4837  | 2673  | 966   | 26.43     | 1.04  | 2   | 3   | 1.56       | 1.44       | 0.36       | 0.38       |
| 26  | 4852  | 2255  | 666   | 25.94     | 1.16  | 3   | 1   | 1.13       | 1.02       | 0.33       | 0.33       |
| 27  | 4942  | 4289  | 3101  | 27.14     | 1.37  | 1   | 1   | 2.56       | 2.28       | 0.34       | 0.39       |
| 28  | 5022  | 8056  | 9171  | 26.17     | 0.68  | 3   | 1   | 1.44       | 1.27       | 0.37       | 0.37       |
| 29  | 5023  | 8224  | 9425  | 26.18     | 1.79; | 2   | 2   | 1.65       | 1.47       | 0.37       | 0.39       |
| 30  | 5074  | 2004  | 446   | 25.40     | 1.10  | 3   | 1   | 1.54       | 1.57       | 0.36       | 0.41       |
| 31  | 5404  | 5620  | 5615  | 25.88     | 1.10  | 3   | 1   | 2.17       | 1.59       | 0.77       | 0.82       |
| 32  | 5560  | 7272  | 8351  | 26.39     | 1.75; | 3   | 2   | 1.56       | 1.49       | 0.42       | 0.44       |
| 33  | 5597  | 9353  | 9848  | 26.53     | 1.04  | 3   | 2   | 2.29       | 1.96       | 0.58       | 0.58       |
Table 1. (Contd.)

| No. | X    | Y    | CoeID | $V_{606}$ | $z$  | eon | Fit | $h_r$, kpc | $h_z$, kpc |
|-----|------|------|-------|----------|------|-----|-----|------------|------------|
| 34  | 5650 | 9326 | 9974  | 25.12    | 1.02 | 2   | 3   | 2.46       | 2.21       |
| 35  | 5692 | 2437 | 833   | 26.88    | 1.55 | 2   | 1   | 1.63       | 1.45       |
| 36  | 5781 | 7049 | 8624  | 25.72    | 0.83 | 1   | 1   | 4.13       | 3.70       |
| 37  | 5811 | 5988 | 6038  | 24.40    | 0.67 | 1   | 2   | 4.48       | 4.27       |
| 38  | 5959 | 3306 | 1612  | 25.72    | 1.76 | 3   | 1   | 1.38       | 1.36       |
| 39  | 6124 | 4282 | 3178  | 26.21    | 1.91 | 3   | 2   | 4.43       | 3.84       |
| 40  | 6178 | 8569 | 9807  | 25.88    | 0.77 | 1   | 2   | 2.62       | 2.45       |
| 41  | 6416 | 8780 | 9834  | 22.55    | 0.43 | 2   | 2   | 2.69       | 3.00       |
| 42  | 6462 | 4440 | 3418  | 26.59    | 3.96 | 3   | 3   | 1.58       | 1.89       |
| 43  | 6486 | 6320 | 6922  | 25.55    | 1.26 | 1   | 3   | 5.26       | 5.29       |
| 44  | 6491 | 7924 | 9139  | 25.83    | 1.84 | 3   | 3   | 1.73       | 1.58       |
| 45  | 6746 | 7127 | 8372  | 23.22    | 0.53 | 3   | 3   | 2.63       | 2.41       |
| 46  | 6785 | 2367 | 735   | 25.72    | 1.12 | 3   | 2   | 1.63       | 1.30       |
| 47  | 6789 | 5075 | 4661  | 26.63    | 0.04 | 2   | 1   | 0.16″      | 0.15″      |
| 48  | 6894 | 7813 | 7737  | 24.39    | 0.53 | 3   | 2   | 1.39       | 1.37       |
| 49  | 6976 | 2949 | 1253  | 27.44    | 2.88 | 3   | 1   | 1.39       | 1.24       |
| 50  | 7079 | 5197 | 4835  | 25.48    | 1.32 | 3   | 2   | 1.55       | 1.44       |
| 51  | 7429 | 5431 | 5408  | 26.95    | 1.42 | 3   | 2   | 1.27       | 1.27       |
| 52  | 7792 | 4286 | 3143  | 25.23    | 1.10 | 3   | 2   | 2.59       | 2.14       |
| 53  | 7856 | 3452 | 1732  | 25.57    | 0.66 | 3   | 2   | 1.62       | 1.65       |
| 54  | 7905 | 3600 | 2017  | 26.53    | 0.63 | 2   | 1   | 1.42       | 1.34       |
| 55  | 8020 | 4758 | 3871  | 26.16    | 0.67 | 1   | 2   | 1.93       | 1.75       |
| 56  | 8614 | 5763 | 5898  | 26.01    | 1.45 | 3   | 3   | 1.23       | 1.24       |
| 57  | 8800 | 4950 | 4321  | 26.24    | 1.10 | 3   | 3   | 1.86       | 1.74       |
| 58  | 9259 | 5065 | 4360  | 24.54    | 0.14 | 3   | 2   | 0.82       | 0.77       |

F606W magnitude in the AB system of magnitudes (Rafelski et al. 2015). Column 6 gives the redshifts, with the photometric $z$ being marked by colons. For galaxy 47 the photometric $z$ is very low (0.04). This value leads to implausible characteristics of the galaxy and, therefore, we do not use it in the subsequent analysis. Columns 7 and 8 in Table 1 provide the classes introduced by us, which reflect the subjective probability that a galaxy belongs to edge-on ones (eon) and the quality of the photometric decomposition (fit) (1 means the highest probability and quality, 3 means a low one).

The decomposition results are summarized in the last columns of the table. (We are interested in the scale lengths of the brightness distribution $h_r$ and $h_z$, so that the surface brightnesses of the galaxies are not discussed in the paper.) For both exponential scale lengths the first and second numbers refer to the $V_{606}$ and $i_{775}$ filters, respectively. For three galaxies (1, 15, and 47) the results in Table 1 are presented in arc-
RESULTS AND DISCUSSION

General Characteristics of the Sample Galaxies

Figure 2 shows the distributions of the galaxies in redshift and apparent $V_{606}$ magnitude. The mean redshift of the galaxies we consider is $\langle z \rangle = 1.23 \pm 0.69$ (here and below, the unbiased sample variance is given as an error). The galaxies with spectroscopic $z$ are, on average, nearer than the objects with photometric estimates ($\langle z \rangle = 1.01 \pm 0.34$ vs. $\langle z \rangle = 1.57 \pm 0.92$) and are brighter (Fig. 2).

For the cosmological model adopted in this paper the redshift $z = 1.2$ corresponds to the time elapsed after the onset of cosmological expansion, $\sim 5$ Gyr. Consequently, the epochs at which we study the galaxies in the HUDF and the regions of the nearby Universe ($z \approx 0$) are spaced more than 8 Gyr apart. It is hoped that on such a long time scale we will be
The means of these distributions are \( \langle V \rangle \) for edge-on nearby galaxies (Bizyaev et al. 2014). The redshift constraint was used, because the photometric \( z \) (only these are known for galaxies at \( z > 2 \)) for distant galaxies are generally less accurate than those for nearer ones. To find the absolute \( B \) magnitudes \( (M(B)) \), we used the results by Sirianni et al. (2005) and for all objects applied the \( k \) correction for an Sc galaxy from Bicker et al. (2004). The mean observed luminosity for the edge-on galaxies in the HUDF is \( (M(B)) = -18^{m}.5 \pm 1^{m}.4 \). Given the correction for internal absorption, which reaches \( \sim 1^{m} - 1^{m}.5 \) for edge-on galaxies (see, e.g., Tully et al. 1998), the luminosities of these galaxies seen face-on, on average, reach values in the range from \( -19^{m} \) to \( -20^{m} \).

Figure 4 shows the distributions of the sample galaxies in \( h_r \) and \( h_z \) expressed in kpc in the \( i_{775} \) filter. The means of these distributions are \( \langle h_r \rangle = 1.97 \pm 0.92 \) kpc and \( \langle h_z \rangle = 0.49 \pm 0.16 \) kpc. If we restrict ourselves only to the objects of eon and fit classes 1 and 2 (the number of such galaxies in the sample is 22), then \( \langle h_r \rangle = 2.39 \pm 0.89 \) kpc and \( \langle h_z \rangle = 0.52 \pm 0.20 \) kpc. The above scale lengths look typical for edge-on nearby galaxies (Bizyaev et al. 2014).

The mean ratio of the radial scale lengths in the \( V_{606} \) and \( i_{775} \) bands is 1.08 \( \pm 0.08 \), implying the existence of a color gradient—the stellar disks of distant galaxies are, on average, bluer to the periphery. This feature is typical for the disks of nearby spiral galaxies. The ratio of the vertical scale lengths in the same filters exhibits no noticeable wavelength dependence: \( \langle h_z(V_{606})/h_z(i_{775}) \rangle = 0.97 \pm 0.07 \). This is also consistent with the data for nearby galaxies (see, e.g., Bizyaev et al. 2014).

**Sample Completeness**

Obviously, our sample of edge-on galaxies in the HUDF is incomplete. This incompleteness should be most pronounced for faint and poorly resolvable galaxies, in which the orientation of the stellar disks with respect to the line of sight is difficult to determine.

We will use two methods to roughly estimate the expected number of edge-on galaxies in the HUDF.

On the one hand, consider the general statistics of galaxies in the HUDF. According to Coe et al. (2006), there are \( \sim 8000 \) galaxies in this field. The total number of spiral galaxies selected by their spectral energy distribution with an apparent F606W magnitude brighter than 27\(^{m}.5 \) (this corresponds to the faintest galaxy in our sample) and \( z \leq 2 \) is 1233. Assuming a random orientation of the galactic planes, we can roughly estimate the relative fraction of edge-on galaxies (with an inclination between the line of sight and the normal to the disk plane \( \geq 85^\circ \)) to be \( | \cos 90^\circ - \cos 85^\circ | = 0.087 \). Consequently, the expected number of edge-on spiral galaxies in the HUDF is \( 1233 \times 0.087 \approx 10^2 \).

On the other hand, we can take the luminosity function of nearby edge-on spiral galaxies and estimate how many such objects should be observed toward the HUDF. For our estimation we took the luminosity function of spiral galaxies based on data.
from the 2dF survey (Kroton et al. 2005). According to Kroton et al. (2005), the total space density of local spiral galaxies in the range of absolute magnitudes from $M(B) = -15^m$ to $M(B) = -21^m$ (Fig. 2) is $0.022 \text{ Mpc}^{-3}$. Consequently, the space density of edge-on galaxies is $0.022 \times 0.087 = 0.002 \text{ Mpc}^{-3}$. Having integrated this space density toward the HUDF (its angular size is $\sim 10^{-6} \text{ sr}$), we found that within $z \leq 2$ about 90 galaxies should be observed in the field. The expected luminosity distribution of these 90 galaxies in luminosity is indicated in Fig. 2 by the dashed line.

It can be seen from Fig. 3 that for bright (with $M(B) \leq -18^m$) objects the number of galaxies selected in the HUDF roughly agrees with the expected one. The observational selection for fainter galaxies is apparently much stronger. Consequently, for bright galaxies our sample is probably relatively complete, while many galaxies can be missed among the fainter objects.

It is worth noting that the above reasoning is not too reliable, because in Fig. 3 we compare the observed luminosities of distant edge-on galaxies with the luminosities of nearby galaxies. Because of their edge-on orientation, the distant galaxies look fainter by $\sim 1^m$ than the face-on galaxies. On the other hand, however, the galaxies at $z \sim 1$ should be brighter than the nearby objects approximately by $1^m$ due to the evolution of their luminosity. Both effects can partly cancel each other out and, therefore, for illustrative

Fig. 4. (Color online) Distributions of the sample galaxies in (a) radial and (b) vertical disk scale lengths (in kpc). The scale lengths are given in the $i_{775}$ filter. Different lines correspond to different subsamples of galaxies (see the caption to Fig. 2).
purposes we still compare the luminosities of the nearby and distant galaxies in Fig. 3.

Another factor that is difficult to take into account is the evolution of the properties of the spiral galaxies themselves. Because of this effect, many of the distant galaxies that look irregular and asymmetric at \( z \sim 1 \) can evolve into typical spiral galaxies with thin stellar disks by \( z \sim 0 \).

**Relative Thickness of the Stellar Disks**

The mean ratio of the radial and vertical exponential disk scale lengths for the entire sample (58 galaxies) in the \( i_{775} \) band is \( \langle h_r/h_z \rangle = 4.02 \pm 1.28 \). If we restrict ourselves only to the objects of classes 1 and 2, which characterize the probability of assignment to edge-on galaxies and the decomposition quality, then \( \langle h_r/h_z \rangle = 4.61 \pm 0.98 \) (22 galaxies). In the \( V_{606} \) filter the corresponding quantities are \( \langle h_r/h_z \rangle = 4.46 \pm 1.45 \) and \( \langle h_r/h_z \rangle = 5.27 \pm 1.23 \).

These mean values look smaller (i.e., the galactic disks are thicker) than those for spiral galaxies in the nearby Universe. For example, in the biggest present-day catalog of edge-on galaxies containing more than 5000 objects (Bizyaev et al. 2014), the mean values of this ratio vary from 6.34 in \( i \) to 7.14 in \( g \) (here we took into account the fact that \( h_z = z_0/2 \); \( g \) and \( i \) are the SDSS\(^1 \) filters). Other samples of edge-on galaxies also suggest thinner stellar disks of nearby spiral galaxies: for example, 7.4 ± 2.6 (the \( I \) filter; de Grijs 1998), 16 ± 4 (Sc/Sd galaxies in the \( R \) filter; Schwarzkopf and Dettmar 2000), 7.3 ± 2.2 (\( I \); Kregel et al. 2002), 9.6 (\( K \); Bizyaev and Mitronova 2002), 7.1 (\( J \); Mosenkov et al. 2010), 8.26 ± 3.44 (De Geyter et al. 2014), and 8.81 ± 2.78 (Peters et al. 2017). In the last two papers the relative disk thicknesses were obtained by simultaneously modeling the galaxies in the SDSS \( g \), \( r \), \( i \), and \( z \) filters. Kregel et al. (2002), De Geyter et al. (2014), and Peters et al. (2017) used the same photometric model as that in our paper to describe the structure of the galaxies. The data from the remaining papers were recalculated by taking into account the ratio \( h_z = z_0/2 \).

Note that we compare the observed relative thicknesses of the galaxies from the HUDF with those for the nearby edge-on galaxies. This is because the stellar disks seen edge-on look more extended due to the integration of radiation along the line of sight. This effect can introduce certain systematics into the radial scale lengths measured by different methods. For example, Padilla and Strauss (2008) and Rodriguez and Padilla (2013) estimated the thickness of spiral galaxies by studying the distribution of galaxies from SDSS in apparent flattening. As the apparent flattening these authors took the SDSS axial ratio found by fitting the galaxies with an exponential model. According to the first and second papers, the true flattening of the disks of spiral galaxies is \( 0.21 \pm 0.02 \) and \( 0.27 \pm 0.009 \), respectively. These values correspond to \( h_r/h_z = 4.8 \) and 3.7 are are close to our data for distant galaxies. On the other hand, our detailed modeling of the structure of nearby edge-on galaxies is in conflict with such large stellar disk thicknesses (see the references above).

Figure 5 shows the positions of our edge-on galaxies with \( z \) and fit classes equal to 1 and 2 on the absolute magnitude–disk scale length ratio plane in the \( i_{775} \) band. The same figure displays the data from the catalog of nearby edge-on galaxies (Bizyaev et al. 2014). The galaxies from the HUDF are seen to be located along the lower envelope of the distribution for nearby spiral galaxies, i.e., where there are the thickest observed disks. Thin stellar disks with an exponential scale length ratio of \( \approx 10 \) are very rare among the galaxies at \( z \approx 1 \).

To a first approximation, the reduced ratio \( h_r/h_z \) for distant galaxies can be explained by two factors: (1) an increased (in absolute terms) thickness of their disks and (2) shorter disks in the radial direction.

Figure 6 compares the characteristics of the galaxies from the HUDF displayed in Fig. 5 with the parameters of nearby objects on the galaxy absolute magnitude–vertical exponential scale length (in kpc) and absolute magnitude–radial scale length (in kpc) planes.

It can be seen from Fig. 6a that the distant spiral galaxies, though with a large scatter, generally follow the luminosity–stellar disk thickness relation for objects in the nearby Universe. For the radial scale lengths (Fig. 6b) the situation looks differently: the characteristics of relatively faint distant galaxies with \( M(B) \geq -18^\text{m} \) lie in the same region as that for nearby objects, while brighter galaxies exhibit relatively short stellar disks.

To check this feature, we plotted the characteristics of 49 spiral galaxies at \( z = 0.7–1.3 \) (\( z \sim 0.92 \pm 0.14 \)) from Miller et al. (2011) on the \( M(B)–h_r \) plane (the open circles in Fig. 6b). The galaxies from Miller et al. (2011) have an arbitrary (not edge-on) orientation and they were selected in the GOODS field of the Hubble Space Telescope. It can be clearly seen from the figure that the distant objects from this paper lie on the \( M(B)–h_r \) plane below the nearby galaxies and form a single sequence with the galaxies from the HUDF that deviates from the sequence for the objects at \( z \sim 0 \). The galaxies from Miller et al. (2011) are, on average, brighter than the objects of our sample.

\(^1\)http://www.sdss.org
Fig. 5. (Color online) Distribution of the galaxies from the HUDF on the galaxy absolute magnitude $M(B)$—radial-to-vertical stellar disk scale length ratio plane in the $i_{775}$ filter (circles). The dots indicate the characteristics of nearby spiral galaxies in the $g$ band from Bizyaev et al. (2014).

Thus, our results in combination with the data from Miller et al. (2011) may provide evidence for differential evolution of the radial sizes of spiral galaxies at $z \lesssim 1$: the low-luminosity objects show no evidence of evolution, while the bright spiral galaxies from $z \sim 1$ to the present epoch should grow by a factor of 2–3. On the other hand, the vertical scale length of spiral galaxies shows no evidence of noticeable evolution at $z \lesssim 1$ (Fig. 6a). Consequently, the increased relative thickness of the stellar disks of spiral galaxies at $z \sim 1$ is explained primarily by the smaller radial sizes of their disks.

The results obtained are consistent with the numerical calculations within ΛCDM cosmology. For example, Brook et al. (2006) showed that at $z \sim 1$ the vertical scale lengths of the stellar disks are already close to the present-day ones, while the radial ones are noticeably shorter. The quantitative agreement between the results looks good. For example, according to Table 2 from Brook et al. (2006), a spiral galaxy at $z \sim 0.9$ with $M(B) = -21^{m}1$ (it will be fainted approximately by 1 mag seen edge-on), $h_r = 2.9$ kpc, and $h_z = 0.63$ kpc will evolve by $z = 0$ into a galaxy with $M(B) = -19^{m}7$, $h_r = 4.1$ kpc, and $h_z = 0.65$ kpc. Thus, between $z \sim 0.9$ and the current epoch the relative thickness of the model galaxy changed from $h_r/h_z = 4.6$ to 6.6, with this change having occurred due to the growth of the galaxy in the radial direction.

Based on numerical simulations, Brooks et al. (2011) showed that the evolution of disk galaxies depends on their mass. The massive spiral galaxies at $z \lesssim 1$ mostly grow in the radial direction; for the low-mass ones the change in their sizes is less pronounced, but, on the other hand, the luminosity changes more dramatically (see Table 3 in Brooks et al. (2011)). The sizes of spiral galaxies increase due to the external accretion of matter and the swallowing of satellites.
CONCLUSIONS

Based on an analysis of the HUDF images, we produced a sample of 58 candidates for edge-on spiral galaxies at a mean redshift $z \sim 1$. For all galaxies we analyzed the 2D brightness distributions in the $V_{606}$ and $i_{775}$ filters and determined the radial and vertical exponential scale lengths of the brightness distribution.

Our main results are as follows.

— The vertical scale length of the stellar disks of spiral galaxies shows no significant evolution at $z \leq 1$.

— The relative thickness of the disks of distant galaxies, on average, exceeds the relative thickness of the disks of nearby spiral galaxies. Thin stellar disks at $z \sim 1$ are apparently very rare.
We obtained evidence for differential evolution of the exponential scale lengths of the stellar disks of galaxies: the bright spiral galaxies at $z \sim 1$ look shortened compared to the nearby objects; the low-luminosity galaxies show no evidence of evolution.

The results of this paper are based on a small sample of galaxies and, undoubtedly, need to be confirmed with a larger number of objects. On the whole, our observational data are consistent with the current views of the evolution of the disk subsystems of galaxies and they can be used to test various models for the evolution of spiral galaxies.

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