THE EVOLUTION OF DISK GALAXIES IN THE GOODS-SOUTH FIELD: NUMBER DENSITIES AND SIZE DISTRIBUTION1

S. RAVINDRANATH,1 H. C. FERGUSON,2,3 C. CONSELICE,4 M. GIAVALISCO,5 M. DICKINSON,2,3 E. CHATZICHRISTOU,5
D. DE MELLO,6 S. M. FALL,2 J. P. GARDNER,6 N. A. GROGIN,1 A. HORNESCHEMEIER,3 S. JOGEE,2
A. KOEKEMOER,2 C. KRETCHEMER,3 M. LIVIO,2 B. MOBASHER,2 AND R. SOMERVILLE2

Received 2003 July 27; accepted 2004 January 16; published 2004 February 25

ABSTRACT

We examine the evolution of the sizes and number densities of disk galaxies using the high-resolution images obtained by the Great Observatories Origins Deep Survey (GOODS) with the Advanced Camera for Surveys on the Hubble Space Telescope. The multiwavelength images are used to classify galaxies based on their rest-frame B-band morphologies out to redshift \( z \sim 1.25 \). In order to minimize the effect of selection biases, we confine our analysis to galaxies that occupy the region of the magnitude-size plane where the survey is \( \sim 90\% \) complete at all redshifts. The observed size distribution is consistent with a lognormal distribution as seen for the disk galaxies in the local universe and does not show any significant evolution over the redshift range \( 0.25 \leq z \leq 1.25 \). We find that the number densities of disk galaxies remains fairly constant over this redshift range, although a modest evolution by a factor of 4 may be possible within the \( 2 \sigma \) uncertainties.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: fundamental parameters — galaxies: structure

1. INTRODUCTION

Disk galaxies constitute about 60\%–80\% of the galaxies in the nearby universe (Buta et al. 1994), and it is very important to understand how they formed and evolved. In recent years, high-resolution images from the Hubble Space Telescope (HST) have proved extremely valuable in obtaining the structural parameters of galaxies out to \( z \sim 1 \). In this Letter, we address the issue of whether or not the size distribution and number density of disk-dominated galaxies evolve with redshift. The evolution of disk galaxies has been explored previously via the magnitude-size \(( M_p, r)\) relation (Schade et al. 1996; Lilly et al. 1998; Roche et al. 1998; Simard et al. 1999; Bouwens & Silk, 2002) and the Tully-Fisher \(( M_p, V)\) relation (Vogt et al. 1996). Based on HST imaging, most studies found evidence of a significant increase \((\sim 1–1.3 \text{ mag})\) in the rest-frame B-band surface brightness of disk galaxies to \( z = 1 \), while Simard et al. (1999) found no evidence of surface brightness evolution once the selection effects of the survey were taken into account. The luminosity-size evolution of disks remains a controversial issue, and the interpretation of any observed evolution with redshift depends crucially on accounting for the selection biases of the survey (Simard et al. 1999; Bouwens & Silk 2002). Lilly et al. (1998) reported that the abundance and size distribution remain constant out to \( z \sim 1 \), for the large disks with scale lengths greater than \( 5 \text{ kpc} \), for which their sample is fairly complete. The space densities at different look-back times provide a key observable to help determine how and when large galaxies like the Milky Way were formed.

The multiwavelength \((B, V, i, z)\) HST Advanced Camera for Surveys images from the Great Observatories Origins Deep Survey (GOODS) serve as an excellent resource to examine the size and number density evolution of disk galaxies with redshift. The availability of a long-wavelength baseline from 4300 to 9000 Å allows us to study galaxy properties consistently in the rest-frame B band for galaxies out to \( z \sim 1.25 \). Also, the large area of the survey provides an ample number of galaxies over the range \( 0.25 \leq z \leq 1.25 \) for studying the number density evolution. We adopt the cosmology defined by \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 0.3 \), and \( \Omega_k = 0.7 \) throughout this Letter.

2. MORPHOLOGICAL ANALYSIS AND IDENTIFICATION OF DISKS

The analysis presented here is based on the first three epochs of observations of the Chandra Deep Field–South (CDF-S) obtained via the GOODS program. The sample consists of all sources from the SEExtractor (Bertin & Arnouts 1996) source catalogs of the GOODS CDF-S region (Giavalisco et al. 2004) with \( z_{\text{spec}} \leq 24.0 \text{ mag} \) and a stellarity index of less than 0.8. These criteria ensure that the signal-to-noise ratio is sufficient for the morphological analysis and excludes the stars. The photometric redshifts for the galaxies are from Mobasher et al. (2004) and are found to be robust (rms \( \leq 0.11 \)) out to \( z \sim 1 \) for objects with \( z_{\text{spec}} \leq 24.0 \text{ mag} \) based on the comparison with available spectroscopic redshifts. The final sample consists of 2781 objects with \( 0.25 \leq z \leq 1.25 \).

We derive the structural parameters of the galaxies through a two-dimensional modeling of the surface brightness distribution using the GALFIT software (Peng et al. 2002). We use a single Sérsic (Sérsic 1968) function to model the brightness profiles, and we use simulations to verify that the Sérsic index, \( n \), can provide a reliable classification of the bulge-dominated and disk-dominated galaxies even at the faint magnitudes. The

\[ z_{\text{spec}} \] denotes an observed AB magnitude in the F850LP filter. The limiting isophote for the source detection was \( \sim 27.5 \text{ mag arcsec}^{-2} \) in the \( z \) band.

---

1 Based on observations obtained with the NASA/ESA Hubble Space Telescope, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under NASA contract NAS5-26555.
2 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.
3 Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218.
4 California Institute of Technology, Mail Code 105-24, Pasadena, CA 91125.
5 Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520.
6 Laboratory for Astronomy and Solar physics, Code 681, Goddard Space Flight Center, Greenbelt, MD 20771.
quality of the best-fit model is judged based on the reduced χ² (χ²_r) value that should be close to unity when the model is a good match to the data. The index, n, is known to correlate with galaxy morphology (Andredakis, Peletier, & Balccells 1995). In Figure 1, we illustrate the classification based on n, using nearby galaxies from the Frei sample (Frei et al. 1996), which have been redshifted artificially to z = 0.5 and z = 1.0 (Conselice 2003). The criterion n < 2.0 allows us to select disk-dominated galaxies (Sbc–Sdm) even when they have morphological complexities such as dust, star-forming regions, etc. However, a few late-type galaxies have high n due to the presence of a bright nucleus, or circumnuclear star formation in the center, and may be missed by our disk selection criterion.

It is encouraging that only a few early-type galaxies migrate to the low-n values, and they usually have large χ²_r values that imply a poor fit to the data.

The structural parameters for the galaxies were measured in the rest-frame B band at all redshifts. When the rest-frame B band is redshifted to wavelengths that fall in the gap between two filters, we use an average of the measurements made in the two filters. We identified 1508 disk galaxies, after excluding about 1% of the galaxies with that have high surface brightness and constitute most of the outliers in our classification scheme. The galaxies that deviate most from their expected galaxy type are labeled as n > 2 and have large χ²_r values because the fits were poor.

3. RESULTS

Magnitude-size relation for disk galaxies —In order to compare the evolution of disks at different redshifts, it is important to consider the effect of selection biases that can artificially introduce evolutionary signatures in the absolute magnitude–size (M_r–r_e) plane shown in Figure 2. From our simulations, we found that the selection in the z band is more than 90% complete for disk galaxies with surface brightness, μ_e ≤ 23.4 mag arcsec⁻², measured within the effective radius. Assuming an exponential profile for the disks, this corresponds to a rest-frame B-band central surface brightness of μ_e > 20.6 mag arcsec⁻² in the highest redshift bin. The z ≤ 24 mag criterion adopted in the sample selection translates to M_r ≤ −19.5 mag in this redshift bin, and the smallest disk size is r_e ≈ 0.8 kpc. Thus, disk galaxies with M_r < −19.5 mag, μ_e ≤ 20.6 mag arcsec⁻², and r_e > 0.8 kpc are almost free of selection biases at all redshifts, and their distribution in the M_r–r_e plane must reflect the actual luminosity or size evolution. Therefore, only disk galaxies satisfying the above criteria (red crosses in Fig. 2) are considered for further analysis. At redshifts z ≥ 1, the surface brightness threshold for 90% completeness is about a magnitude brighter than the Freeman value. The small number of disks with luminosities M_r < −21 mag in the lowest redshift bin is striking even after accounting for the difference in comoving volumes in the various redshift bins. There is a class of high surface brightness disks with M_r < −21.5 mag and r_e < 4 kpc that becomes dominant at z ≥ 1; a similar observation of high surface brightness disks at z ≥ 0.9 was also reported by Simard et al. (1999). These objects could be among the most strongly evolving disk populations from z ~ 1 to the present.
In Figure 3, the luminosity function (LF) is presented for the “selection-free” disk galaxies in all redshift bins along with a representative “nonevolving” LF. Our selection criteria restrict the analysis to the most luminous disks, and the observed LF at $z < 1$ is well represented by a nonevolving LF over the range of luminosities considered. However, at $z > 1$, the number of luminous disks with $M_B < -21$ mag is marginally higher than expected from the nonevolving LF, and the observed points show a relative shift toward higher luminosities.

Size distribution of disk galaxies—Overall, the size distribution (SD) for disk galaxies is consistent with a lognormal distribution, and there is no noticeable size evolution with redshift within our sample (Fig. 4). To examine the effect of the selection and measurement biases on the observed SD at various redshifts within the sample, we carried out simulations by inserting artificial disk galaxies in the GOODS images (see § 2). The disk galaxies in the local universe show a lognormal size distribution and a luminosity-size relation, $r_e \propto L^{-\beta} \sim L^{1/3}$ (de Jong & Lacey 2000). We adopt this analytical form, and the LF discussed in the previous section, for the input nonevolving luminosity–size distribution function for galaxies in our simulations. After applying the same selection function to the simulated galaxies as done for observed galaxies, the sizes are remeasured for the selection-free sample. At all redshifts, the surface brightness threshold adopted for the selection affects the SD at large radii, and the peak of the distribution shifts to smaller sizes. The measured sizes are in good agreement with the input sizes in the simulations for $z < 1.00$ but are biased toward larger sizes at higher redshifts. For the nonevolving model, this occurs because galaxies become increasingly fainter at high redshifts and because the uncertainties in the background estimation are larger. Thus, for the observed galaxies, the SD is not significantly affected by the selection or measurement bias for small disk sizes ($r_e < 4$ kpc) at $z < 1$. But at higher redshifts, given the nature of the measurement bias, an evolution in the SD due to the small disks cannot be distinguished from the effect of luminosity evolution that can make disks brighter and reduce the bias.

Number densities of disk galaxies—The observed number density of disk galaxies (Fig. 5) that are free of selection biases in the GOODS CDF-S field is found to remain almost unchanged out to redshift $z = 1.25$ within the uncertainties. We divided the sample into small disks ($r_e < 4$ kpc) and large disks ($r_e \geq 4$ kpc) to look for differences in their relative abundances. Neither sample shows strong evolution within the uncertainties.

Although a direct comparison with the LF of disk galaxies at $z = 0$ (de Jong & Lacey 2000) would be ideal, the difference in the sample selection makes such a comparison nontrivial, and we defer such a comparison to a future paper. For simplicity, we adopt the same functional form for the model nonevolving LF to facilitate a comparison within the GOODS data set.

---

Fig. 3.—Observed LF (filled circles) for disk galaxies chosen to be free of selection biases from Fig. 2, presented along with the Poisson error bars. A nonevolving LF (solid line) similar to that observed for local spiral disks (de Jong & Lacey 2000) is shown for reference and is characterized by $M_B^* = -20.6$ mag, $\alpha = -0.90$. The normalization adopted for the nonevolving LF has been adjusted to match the total number of galaxies at $0.50 \leq z \leq 0.75$ and is held fixed for the other redshift intervals to look for evolutionary signatures within the sample.

Fig. 4.—Histograms showing the observed size distribution along with the Poisson error bars for the disk galaxies that are free of selection biases. The curves show the effect of selection (dotted line) and measurement (solid line) on an input nonevolving SD (solid line) based on simulations. The input lognormal distribution (prior to selection and measurement) with a peak at $r_e = 6$ kpc and width $\sigma(\ln r_e) = 0.5$ provides a good match to the size distribution observed at $0.50 < z < 0.75$ after the selection criteria is applied, and it is held fixed for the other redshifts; the normalization has been adjusted to match the number of galaxies in this redshift bin. The selection causes the peak of the lognormal distribution to shift to smaller sizes ($r_e = 4$ kpc). Measurement biases become significant only in the highest redshift bin.

Fig. 5.—Observed number densities of all disk galaxies (filled squares, solid line) within the selection-free region in Fig. 2, shown as a function of redshift along with the statistical errors. The number densities of small disks ($r_e < 4$ kpc, open circles, dashed lines) and large disks ($r_e \geq 4$ kpc, filled circles, dotted lines) do not show significant evolution in their relative abundance with redshift.
except for a mild increase in the number of small disks at $z \sim 0.8$. Assuming that the evolution in number density can be expressed in the form $n(z) \propto (1 + z)^\alpha$, a formal linear regression analysis gives $\alpha = 0.08 \pm 0.23$ for all disks, and $\alpha = 0.00 \pm 0.27$ and $0.20 \pm 0.39$ for the small and large disks, respectively. In all cases, the best fit favors an almost constant number density over the whole redshift range. However, a factor of 4 change in the number densities of small disks cannot be ruled out within the 2 $\sigma$ uncertainties of the obtained fits.

The same is true for the large disks if we exclude the lowest redshift bin where the uncertainty is large. Thus, ignoring the possible effects of luminosity evolution at $z > 1$, it appears that the population of disk galaxies could have undergone only very modest evolution in their number densities from $z = 0.25$ to $z = 1.25$. In order to check for contamination from bulge-dominated galaxies that scatter into the sample at faint magnitudes, we redid the analysis using only those galaxies with $n \leq 1.5$, which have negligible bulge components, and obtained very similar results.

4. DISCUSSION

In the context of the evolution of disk galaxies in the $M^p r_e$ plane, it is important to investigate the effects of a B-band surface brightness increase by $\sim 1.1$–1.5 mag out to $z \sim 1$, claimed by some studies and contradicted by others (see § 1). To allow direct comparisons at different redshifts within the GOODS data, we confined our analysis to galaxies with $M_B < -19.5$ mag and $\mu^p_B < 20.6$ mag arcsec$^{-2}$, such that they are not affected by selection biases in any redshift. For this sample, we do not see any significant evolution in the mean B-band surface brightness ($\Delta \mu^p_B < 0.4$). These results are in agreement with Simard et al. (1999), who apply a uniform selection function from the highest to lowest redshift bins. In contrast, the strong surface brightness evolution seen by Bouwens & Silk (2002) is based on their comparison of samples that span different ranges of luminosity and surface brightness at different redshifts. If we include all the disks in our data within the apparent magnitude and surface brightness limits for 90% completeness in the $z$ band, we find an increase in the mean B-band surface brightness by $\sim 0.93$ mag from $z = 0.2$ to $z = 1$. Such a selection made based on apparent magnitude and size translates to different surface brightness thresholds in the intrinsic $M^p r_e$ plane at different redshifts. For example, at low redshifts ($z < 0.5$) most of the disk galaxies chosen based on the above criteria have average $\mu^p_B$ close to the Freeman value, while at higher redshifts the average $\mu^p_B$ for the selected disks shifts to brighter magnitudes. The interpretation of the results in this case would thus depend on comparison with disk evolution models; alternatively, a comparison can be made using like samples at different redshifts, which is the approach used here.

The size distribution of disks over the redshift range $0.25 < z < 1.00$ is found to remain unchanged and exhibits a lognormal behavior similar to disk galaxies at low redshifts (de Jong & Lacey 2000; Shen et al. 2003). This also agrees with the expectations from the hierarchical models of disk formation (Fall & Efstathiou 1980). However, we note that the observed peak and shape of the SD at large $r_e$ may be partly affected by the surface brightness threshold (Fig. 2) that defines the selection. The evolution of the observed SD at $z > 1$ within the GOODS sample, either due to a mild increase in the number of small-sized disks ($r_e < 4$ kpc) or due to luminosity evolution that makes the disks appear brighter at higher redshifts, cannot be distinguished given the measurement biases. Also, the scatter of bulge-dominated systems into the sample can lead to a similar effect and may pose a challenge to using the simple $n < 2$ criteria for disk galaxy classification at high redshifts.

From the observed number densities and luminosity-size distributions, we conclude that the population of luminous ($M_B < -19.5$ mag) disk galaxies with the sizes ranging from 0.8 to 10 kpc were present with roughly the same abundance at $z = 1$ as at low redshifts ($z \sim 0.2$) and are likely to have undergone only a modest luminosity evolution. This would require a formation epoch earlier than $z = 1$ for these galaxies. Albeit based on a small number of galaxies, it is interesting that there is evidence of large disks at a mean redshift of $z = 2.3$ (Labbé et al. 2003) with roughly the same abundance as seen for the large disks at $z \sim 1$ in our data. Whether or not this implies that massive systems like the Milky Way were already in place at that epoch can be addressed with additional kinematic information to constrain the mass-to-light ratios. A more detailed analysis based on the full GOODS data will be presented in a future paper.

This work was supported by grant GO09583.01-96A from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5-26555. We thank C. Y. Peng and T. Dahlen for useful discussions, and the referee for helpful comments.

REFERENCES

Andredakis, Y. C., Peletier, R. F., & Balcells, M. 1995, MNRAS, 275, 874
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bouwens, R., & Silk, J. 2002, ApJ, 568, 522
Buta, R., Mita, S., de Vaucouleurs, G., & Corwin, H. G., Jr. 1994, AJ, 107, 118
Conselice, C. J. 2003, ApJS, 147, 1
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J., Pasturel, G., & Fouqué, P. 1991, Third Reference Catalogue of Bright Galaxies (New York: Springer)
de Jong, R. S., & Lacey, C. 2000, ApJ, 545, 781
Fall, S. M., & Efstathiou, G. 1980, MNRAS, 193, 189
Freeman, K. C. 1970, ApJ, 160, 811
Frei, Z., Guhathakurta, P., Gunn, J. E., & Tyson, J. A. 1996, AJ, 111, 174
Gaivalisco, M., et al. 2004, ApJ, 600, L93
Graham, A. W. 2001, AJ, 121, 820
Labbé, I., et al. 2003, ApJ, 591, L95
Lilly, S. J., et al. 1998, ApJ, 500, 75
Mobasher, B., et al. 2004, ApJ, 600, L167
Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2002, AJ, 124, 266
Roche, N., Ranatunga, K., Griffiths, R. E., Im, M., & Naim, A. 1998, MNRAS, 293, 157
Schade, D., Lilly, S. J., Le Fèvre, O., Hammer, F., & Crampton, D. 1996, ApJ, 464, 79
Shen, S., Mo, H. J., White, S. D. M., Blanton, M. R., Kauffmann, G., Voges, W., Brinkmann, J., & Csabai, I. 2003, MNRAS, 343, 978
Simard, L., et al. 1999, ApJ, 519, 563
Sérsic, J. L. 1968, Atlas de Galaxias Australes (Córdoba: Obs. Astron., Univ. Nac. Córdoba)
Vogt, N. P., Forbes, D. A., Phillips, A. C., Gronwall, C., Faber, S. M., Illingworth, G. D., & Koo, D. C. 1996, ApJ, 465, L15