A STUDY OF EDGE-ON GALAXIES WITH THE HUBBLE SPACE TELESCOPE ADVANCED CAMERA FOR SURVEYS. II. VERTICAL DISTRIBUTION OF THE RESOLVED STELLAR POPULATION

Anil C. Seth and Julianne J. Dalcanton
Astronomy Department, University of Washington, Box 351580, Seattle, WA 98195; seth@astro.washington.edu, jd@astro.washington.edu

AND

Roelof S. de Jong
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; dejong@stsci.edu

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ABSTRACT

We analyze the vertical distribution of the resolved stellar populations in six low-mass (\(V_{\text{max}} = 67-131 \text{ km s}^{-1}\)), edge-on, spiral galaxies observed with the Hubble Space Telescope Advanced Camera for Surveys. In each galaxy we find evidence for an extraplanar stellar component extending up to 15 scale heights (3.5 kpc) above the plane, with a scale height typically twice that of two-dimensional fits to \(K_s\)-band Two Micron All Sky Survey images. We analyze the vertical distribution as a function of stellar age by tracking changes in the color-magnitude diagram. The young stellar component (\(\approx 10^8 \text{ yr}\)) is found to have a scale height larger than the young component in the Milky Way, suggesting that stars in these low-mass galaxies form in a thicker disk. We also find that the scale height of a stellar population increases with age, with young main-sequence stars, intermediate-age asymptotic giant branch stars, and old red giant branch (RGB) stars having successively larger scale heights in each galaxy. This systematic trend indicates that disk heating must play some role in producing the extraplanar stars. We constrain the rate of disk heating using the observed trend between scale height and stellar age and find that the observed heating rates are dramatically smaller than in the Milky Way. The color distributions of the RGB stars well above the midplane indicate that the extended stellar components we see are moderately metal-poor, with peak metallicities around \([\text{Fe/H}] = -1\) and with little or no metallicity gradient with height. The lack of metallicity gradient can be explained if a majority of extraplanar RGB stars were formed at early times and are not dominated by a younger heated population. Our observations suggest that, like the Milky Way, low-mass disk galaxies also have multiple stellar components. In its structure, mean metallicity, and old age, the RGB component in these galaxies seems analogous to the Milky Way thick disk. However, without additional kinematic and abundance measurements, this association is only circumstantial, particularly in light of the clear existence of some disk heating at intermediate ages. Finally, we find that the vertical dust distribution has a scale height somewhat larger than that of the main-sequence stars.

Key words: dust, extinction — galaxies: formation — galaxies: individual (IC 5052, NGC 55, NGC 4144, NGC 4244, NGC 4631, NGC 5023) — galaxies: spiral — galaxies: structure

Online material: color figures

1. INTRODUCTION

Galactic structure has long been recognized as a key constraint on theories of galaxy formation. The presence of two distinct components—disks and spheroids—suggests that at least two separate physical mechanisms are active during the formation of spiral galaxies. Within the Milky Way, however, detailed analyses of the kinematics and chemistry of nearby stars have revealed additional components: a thin disk with scale heights dependent on age, a thick disk, and a stellar halo. Each of these components places unique constraints on the Galaxy’s evolution. In particular, the ages and metallicities of the old thin disk, thick disk, and halo indicate that they are remnants of the initial stages in the assembly of the galaxy and thus constrain the early evolution of galaxies.

Several scenarios for the creation of the old thin and thick disks are consistent with current observations in the Milky Way. These scenarios can be categorized into three main types: (1) the creation of a thick disk from a thin disk through heating by molecular clouds, spiral arms, star formation, or accretion events (e.g., Spitzer & Schwarzschild 1951; Barbanis & Woltjer 1967; Lacey 1991; Kroupa 2002; Quinn et al. 1993; Gnedin 2003), (2) the slow collapse of the proto-Galaxy, forming the thick and thin disks in succession (e.g., Eddington 1962; Gilmore 1984), and (3) the formation of a thick disk from mergers, either by direct accretion of stars or by in situ formation from accreted gas (e.g., Bekki & Chiba 2001; Gilmore et al. 2002; Abadi et al. 2003; Brook et al. 2004). In this last scenario the thin disk would likely form by a settling of gas from the merger events. It is widely assumed that the stellar halo forms from accreted satellites (see the review by Freeman & Bland-Hawthorn 2002). Determination of which processes are important in galaxy formation requires the study of stellar components in other galaxies.

Unfortunately, detailed analyses of older stellar components are difficult outside the Milky Way. Some thick disks and stellar halos have been identified using broadband surface photometry (e.g., Burstein 1979; Tsikoudi 1979; Dalcanton & Bernstein 2002; Pohlen et al. 2004; Zibetti et al. 2004), but their low surface brightness precludes all but the most cursory study of their structure and stellar content. Recently, Hubble Space Telescope (HST) imaging has begun to allow richer analyses of the resolved stars in the thick disk and halo (Brown et al. 2003; Tikhonov et al. 2005; Mould
2. REVIEW OF THE GALAXY PROPERTIES

Table 1 shows the position, type, maximum circular velocity ($V_{\text{max}}$), distance modulus ($m - M_{\text{TRGB}}$), scale length ($h_\text{s}$), and $K_s$-band half-light height ($z_{1/2}$) of the six galaxies that we discuss in this paper. The latter two parameters were determined from two-dimensional model fits to 2MASS $K_s$-band data presented in Paper I. The vertical component of these models is defined using the distribution of an isothermal population of stars (van der Kruit & Searle 1981):

$$\Sigma(z) \propto \text{sech}^2 \left( \frac{z}{z_0} \right),$$

where $\Sigma(z)$ is the surface brightness or density at a position $z$ above the midplane and $z_0$ is the scale height. We use this functional form to fit vertical distributions throughout this paper.

Note, however, that this is one of many equations commonly used to describe the vertical distribution of stars in galaxies, a good overview of which can be found in Pohlen et al. (2000). Most of these functional forms vary near the midplane but have similar exponential declines at large disk heights. When comparing galaxies in this paper, the disk heights are normalized by the $z_{1/2}$ parameter, which gives the height containing 50% of the $K_s$-band light in the model fits. It is related to $z_0$ by $z_{1/2} = 0.5z_0$, and is similar to the exponential scale height $h_\text{s}$, which at large scale heights is equal to $\frac{2}{3}z_0$ (van der Kruit & Searle 1981). The values of $z_{1/2}$ for the six galaxies range from 160 to 280 pc. For comparison, the Milky Way thin disk has exponential scale heights ranging from ~100 pc at young ages (Schmidt 1963) to 330 pc at older ages (Chen et al. 2001).

All six galaxies are within 8 Mpc and are type Sc or later. The maximum circular velocities are all below 135 km s$^{-1}$, suggesting that these objects are closer in mass to the LMC than to the Milky Way. We note that all the galaxies except NGC 4631 have circular velocities well below 120 km s$^{-1}$, which appears to mark a break in the dust properties (Dalcanton et al. 2004) and current metallicity (Garnett 2002) in spiral galaxies. The scale lengths of our sample galaxies range from 0.9 to 1.6 kpc, ~2–3 times smaller than the Milky Way scale length.

None of the galaxies has an apparent bulge component, although NGC 4244 does have a prominent central stellar cluster, which is clearly visible in the ACS and 2MASS $K_s$-band images.

Our observations include eight $HST$ ACS fields in the six galaxies shown in Table 1 and are described fully in Paper I. These observations were obtained to study the dust-lane properties of these galaxies and hence are centered on the galaxy midplane. The dimensions of these eight fields are given in Table 2, which shows the minimum and maximum disk radius in terms of the scale length and the minimum and maximum disk height in terms of $z_{1/2}$. In general, each field is located close to the center of the galaxy. However, two of the galaxies, NGC 55 and NGC 4631, have additional fields located farther out in the disk that are given a “DISK” suffix. Note that many of the galaxies lie diagonally across the chip, meaning that the extremities of the ranges given in Table 2 are not well sampled. In this paper we focus on the vertical distributions of the stars and, where not otherwise noted, analyze all data at the same disk height together.

The approach proposed above is valid as long as the scale height of the disk components does not vary substantially with age.

2 The Milky Way thin and thick disk scale lengths are rather uncertain, with recent values ranging between 2 and 4 kpc (e.g., Ng et al. 1996; Mendez & van Altena 1998; Ojha 2001). We use a scale length of 3 kpc for comparisons to the Milky Way made in this work.

### Table 1: Galaxy Sample Properties

| Galaxy     | R.A. (J2000.0) | Decl. (J2000.0) | Inclination (deg) | Type   | $V_{\text{max}}$ (km s$^{-1}$) | $m - M_{\text{TRGB}}$ | $h_\text{s}$ (arcsec) | $h_\text{s}$ (kpc) | $z_{1/2}$ (arcsec) | $z_{1/2}$ (pc) |
|------------|----------------|----------------|------------------|--------|------------------|-------------------|-------------------|-----------------|-----------------|----------------|
| IC 5052    | 20 52 02.9     | -69 11 45      | 89               | SBcd   | 28.90            | 53.87             | 1.57              | 3.73            | 214             |
| NGC 55     | 00 14 54.4     | -39 11 59      | 80               | SBm    | 26.63            | 93.30             | 0.96              | 23.34           | 240             |
| NGC 4144   | 12 09 58.3     | +46 27 28      | 83               | SBc    | 29.36            | 30.56             | 1.10              | 6.96            | 251             |
| NGC 4244   | 12 17 29.5     | +37 48 28      | 84.5             | Sc     | 28.20            | 84.27             | 1.78              | 12.15           | 257             |
| NGC 4631   | 12 42 07.7     | +32 32 33      | 85               | SBEd   | 29.42            | 35.49             | 1.32              | 7.54            | 280             |
| NGC 5023   | 13 12 11.7     | +44 02 17      | 88               | Sc     | 29.10            | 39.81             | 1.28              | 5.10            | 160             |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The right ascension, declination, TRGB distance moduli, $h_\text{s}$, and $z_{1/2}$ are taken from Paper I. Galaxy types and $V_{\text{max}}$ are from HYPERLEDA/LEDA (Paturel et al. 1995, 2003). Inclinations are taken from Becker et al. (1988), Hummel et al. (1986), Martin (1998), Olling (1996), Hummel & Dettmar (1990), and de Grijis & van der Kruit (1996) (in the same order as in the table).
radius, an assumption that has been verified through observations of edge-on galaxies (e.g., van der Kruit & Searle 1981; Pohlen et al. 2004). We note, however, that there are some analyses that indicate that the scale height of galaxies flares with increasing radius, both in our own Galaxy (López-Corredoira et al. 2002) and in edge-on galaxies (de Grijs & Peletier 1997; Narayan & Jog 2002). However, de Grijs & Peletier (1997) show that in their sample of edge-on galaxies, late-type galaxies such as those observed here have little or no flaring. In one of our galaxies, NGC 4244, flaring of the $\text{H}_\text{i}$ gas by a factor of $\sim 3$ is seen between radii of 8 and 13 kpc (Olling 1996). Even if similar flaring occurs in the stellar distribution, the star counts at the disk heights we consider here are still dominated by stars located (radially) near the center of the galaxy. We note that we do see some evidence for modest flaring in our two DISK fields, which lie at large radii (see § 4.2.1).

In Paper I we presented the CMDs for each of the galaxy fields discussed here. These are reproduced in Figure 1, which shows the $F606W - F814W$ color versus the $F814W$ magnitude. All

| Field      | Number of Stars | $R_{\text{min}}$ ($R/\text{hr}$) | $R_{\text{max}}$ ($R/\text{hr}$) | $z_{\text{min}}$ ($z/z_{1/2}$) | $z_{\text{max}}$ ($z/z_{1/2}$) |
|------------|-----------------|-------------------------------|-----------------------------|-------------------------------|-------------------------------|
| IC 5052    | 68,636          | $-2.9$                        | $1.9$                       | $-22.1$                       | $15.6$                        |
| NGC 55     | 281,536         | $-1.6$                        | $1.4$                       | $-5.8$                        | $5.3$                         |
| NGC 55-DISK| 253,108         | $3.3$                         | $6.2$                       | $-7.3$                        | $5.5$                         |
| NGC 4144   | 60,552          | $-2.3$                        | $5.9$                       | $-18.7$                       | $14.6$                        |
| NGC 4244   | 121,238         | $-1.4$                        | $1.2$                       | $-6.8$                        | $10.5$                        |
| NGC 4631   | 104,940         | $-3.1$                        | $3.4$                       | $-17.8$                       | $10.2$                        |
| NGC 4631-DISK | 97,656   | $-10.1$                      | $-1.6$                      | $-21.2$                       | $14.8$                        |
| NGC 5023   | 42,293          | $-2.7$                        | $3.1$                       | $-18.1$                       | $25.3$                        |

![CMDs of each galaxy. Contours are used where the density of points becomes high. The contours are drawn at densities of 75, 100, 150, 200, 250, 350, 500, 750, 1000, and 1500 stars per 0.1 mag and color bin. The bottom right panel contains a key to the gray lines, which demarcate sections of the CMD. The line across the bottom of each panel shows the 20% completeness limit in bright regions of the galaxy (see § 2.1 for details), and the other lines show the regions used in each galaxy for the MS/HeB, AGB, and RGB stars.](image-url)
magnitudes in this paper are given in the VEGAmag system (see Paper I for details). Each of the CMDs show plumes at F606W − F814W colors of ∼0.1 and ∼1.3, which are typical of young main-sequence (MS) and helium-burning (HeB) stars, respectively. An old RGB can be seen in each galaxy at colors of ∼1, and an intermediate-age asymptotic giant branch (AGB) extends from the TRGB to redder colors. Further details on the components can be found in §4.1 and in Paper I. The boxes shown in Figure 1 isolating these components are discussed in greater detail in §4.

2.1. Completeness Corrections

As described in Paper I, we conducted extensive artificial star tests to characterize the completeness in each field as a function of magnitude, color, and location. The galaxies in our sample have high surface brightnesses near their midplanes, making the completeness there much lower (see Fig. 2 from Paper I). The goal of this paper is to analyze the vertical distribution of stellar populations, and therefore, correcting for this varying completeness is critical.

For each field, over 5 million artificial stars were inserted at random positions, with F606W magnitudes between 18 and 29 and F606W − F814W colors between −1 and 3. These stars were then run through the same pipeline used to determine the stellar photometry. Artificial stars that coincided with actual sources were considered detected only if the input magnitude of the artificial star was brighter than the actual source in both bands.

To enable completeness corrections for individual stars, we determined our completeness for the artificial stars in bins of magnitude, color, and local surface brightness. For the magnitude and color, we used 0.15 mag wide bins. At its steepest, the completeness as a function of magnitude varies by at most 6% over 0.15 mag, so any error introduced by the binning should be smaller than that. We then determined the size of the surface brightness bins such that there would be ∼50 stars in each final bin. Determining the completeness from 50 stars gives a random error in the completeness of ∼6%. An aperture around each star from 11 to 14 pixels was used to determine the local surface brightness. We determined the surface brightness level from the F606W image so as to include the effects of the H α region emission visible in a number of galaxies (most notably NGC 55, which therefore has the brightest completeness level in Fig. 2). This emission is not seen at all in the F814W images due to the lack of strong emission lines in the F814W bandpass. Using this binned completeness function, we are able to determine the completeness of any individual star based on its color, magnitude, and local surface brightness level to within ∼10%. In the stellar density profiles presented in §§3 and 4, the completeness corrections are up to 200% near the midplane but fall to ≤30% at z/2r_12 > 3.

In addition to correcting for the completeness, magnitude limits must also be set to ensure that we are not using stars fainter than we can detect in the higher surface brightness regions of the image (i.e., the midplane). We therefore choose to limit our analysis to regions of the CMD that fall above a conservative 20% completeness limit in regions of high surface brightness. Figure 2 shows the 20% completeness limits for the brightest regions in each field. As can be seen, the completeness limit rises toward redder colors and steepens at colors redder than F606W − F814W = 1. To make a smooth boundary that is easily applied to our data, we fit the 20% completeness curves to two lines intersecting at F606W − F814W = 1. Table 3 shows the results of these fits, by giving the completeness limit at F606W − F814W = −1 (F814Wlim,−1), 1 (F814Wlim,1), and 3 (F814Wlim,3). We use these limits throughout this paper to ensure that comparisons made between stellar populations at different disk heights are valid.

We note here that although we can correct for incompleteness due to crowding, we cannot correct for the attenuation of stars by dust. We show in §4 that all the galaxies in our sample are optically thick near their midplanes. Therefore, at low galactic latitudes, our completeness-corrected stellar census falls short of the true number of stars.

3. VERTICAL DISTRIBUTION OF STARS

We demonstrate in this section that there are significant numbers of stars well above the planes of all our disks and that the profiles of these stars do not fit the profiles expected from the ground-based K_s-band galaxy fits.

In Figure 3 we present the completeness-corrected surface density profiles of all the detected stars (Σ_{all}) above the completeness limits given in Table 3. Two lines are shown for each galaxy, giving the profile on both sides of the disk. To determine the surface density, stars were binned as a function of scale height. After binning, the completeness-corrected number of stars was...
Fig. 3.—Surface density of stars as a function of height from the midplane. Curves have been completely corrected as described in the text. Each galaxy has two lines, one above and one below for the plane. The dashed lines indicate stellar distributions with scale heights 1 and 2 times that of the $K_s$-band fit to the disks. The dot-dashed lines indicate the regions in the NGC 4631 fields where contamination of stars from the companion NGC 4627 is significant. [A color version of this figure, enabling identification of individual galaxies, can be found in the electronic edition of the Journal.]

divided by the area of the bin to obtain the surface density. Only bins with an area of $>300$ arcsec$^2$ are plotted.

Figure 3 shows that we trace the stellar component of each galaxy out to large disk heights, with several galaxies being traced out beyond 10$z_{1/2}$. The profiles in general are fairly symmetric, the most notable exceptions being NGC 4631 and NGC 4631-DISK. These fields are contaminated on one side (dot-dashed lines) by the presence of the companion galaxy NGC 4627 (see Fig. 3 from Paper I). The decrease of the profiles with increasing scale height out to the edge of the fields strongly suggests that the profiles remain above the surface density of foreground Galactic stars and background unresolved dwarf galaxies in our magnitude range. Only above 10$z_{1/2}$ in IC 5052 and NGC 5023 is there some evidence for the leveling off that would be expected as we reach the foreground/background level. Note that the galaxies are all at Galactic latitudes above 35°. We therefore can safely assume that a vast majority of stars in our images are located in the host galaxies, and we make no corrections for foreground/background sources.

The dashed lines in Figure 3 show sech$^2$ profiles with scale heights 1 and 2 times the measured $K_s$-band scale height (note that because the plot is scaled by the $K_s$-band scale height, these profiles are the same for each galaxy). As described in detail in Paper I, models were fitted using a Levenberg-Marquardt algorithm with uniform weighting on all unmasked pixels to $K_s$-band 2MASS data. Because the 2MASS surface photometry has a limiting isophote of $K_s$ $\sim$ 20.0 mag arcsec$^{-2}$, only relatively high surface brightness features could be fitted. The typical $K_s$-band peak surface brightness of our galaxies is $\sim$ 18 (Paper I, Table 2), which means that galaxies are only detected in the $K_s$-band images out to a few $z_{1/2}$ from the midplane. Although the $K_s$-band light is often thought to be dominated by the RGB stars that trace an old stellar population, we show in §4 that in these low-mass, late-type galaxies, it more closely traces the young and intermediate-age populations and is thus dominated by red supergiant and AGB stars.

Figure 3 shows that the outer portions of the stellar density profiles of the galaxies appear to be broader than indicated by the $K_s$-band scale height. To quantify this, we fitted the stellar density profiles between $5z_{1/2}$ and $10z_{1/2}$ on each side of the midplane in each galaxy. Only profiles with data beyond 8$z_{1/2}$ were fitted (thus excluding NGC 55, NGC 55-DISK, and one side of NGC 4244). In the Milky Way, the stellar profile deviates from the thin-disk profile beyond $\sim$ 1 kpc above the plane (Gilmore & Reid 1983). For our galaxies, $5z_{1/2}$ is $\sim$ 1 kpc. Therefore, we would expect our fitting range to be sensitive to a possible thick-disk component in these galaxies. The scale heights of these fits above and below the midplane are shown in the third and fourth columns (respectively) of Table 4. All the fitted stellar profiles are significantly broader (1.5–2.4 times) than the $K_s$-band scale height. This observation strongly suggests that these galaxies contain a more broadly distributed stellar component not traced by the $K_s$-band 2MASS images.

We note that the fitted scale heights, both in the $K_s$ band and using stellar density profiles, can differ from the true scale height due to a number of factors. First, dust attenuation can obscure light near the midplane of the galaxy. In the $K_s$ band this attenuation should be small, and we ameliorate this problem in the fits presented here by avoiding the midplane. Second, the galaxies

### TABLE 4

| Field | $z_0$ (pc) | $K_s$ | All+ | All− | MS | AGB | RGB | $h_z/|z_0,MS|$ | $h_z/|z_0,AGB|$ | $h_z/|z_0,RGB|$ |
|-------|----------|------|------|------|----|-----|-----|---------------|---------------|---------------|
| IC 5052 | 390      | 767 ± 30 | 686 ± 44 | 261 ± 11 | 467 ± 6 | 655 ± 6 | 6.0 | 3.4 | 2.4 |
| NGC 55 | 437      | 327 ± 24 | 644 ± 10 | 701 ± 3 | 2.9 | 1.5 | 1.4 |
| NGC 55-DISK | 437 | 526 ± 1  | 741 ± 15 | 999 ± 6 | 1.8 | 1.3 | 1.0 |
| NGC 4144 | 457   | 940 ± 41 | 965 ± 15 | 374 ± 27 | 699 ± 16 | 934 ± 18 | 2.9 | 1.6 | 1.2 |
| NGC 4244 | 468      | 740 ± 40 | 443 ± 24 | 551 ± 9 | 5.5 | 4.0 | 3.2 |
| NGC 4631b | 510      | 927 ± 46 | 895 ± 51 | 1154 ± 194 | 2.6 | 1.5 | 1.1 |
| NGC 4631-DISKb | 510 | 1131 ± 50 | 1200 ± 1 | 1387 ± 73 | 2.6 | 1.5 | 1.0 |
| NGC 5023b | 291      | 505 ± 32 | 534 ± 26 | 204 ± 6 | 289 ± 6 | 391 ± 4 | 6.3 | 4.4 | 3.3 |

*a* In IC 5052 and NGC 5023, MS, AGB, and RGB fits excluded disk heights below 1.5$z_{1/2}$. Fits for all other galaxies excluded disk heights below 3$z_{1/2}$.

*b* Negative values of $z$ excluded beyond 2 kpc due to the presence of the companion galaxy NGC 4627.
may not be perfectly edge-on. Based on previous observations, the least inclined of the galaxies is NGC 55, which has an $\sim 80^\circ$ inclination (Hummel et al. 1986). This would give a fitted scale height $\sim 30\%$ greater than the intrinsic disk scale height. We also note that NGC 55 and NGC 4631 are fairly irregularly shaped, making the fits to these galaxies less reliable than for the other four galaxies.

4. VARIATION IN DISTRIBUTION WITH STELLAR POPULATION

We now turn our analysis to stars selected in regions of our CMDs that isolate stellar populations with different ages. Using this method we show that the older stellar populations have an increasing scale height. In § 4.3 we examine the variation of scale height in the context of disk heating models. We then present simplistic dust models in § 4.4 and show that the dust extinction in these galaxies is distributed in a component that is broader than the young stellar populations.

4.1. Selection of CMD Regions

We attempt to separate our data into young, intermediate-age, and old stellar populations by selecting stars from different regions in the CMD. The young stars are found in the MS component and in the red and blue HeB sequences (see Paper I, Fig. 1) for a schematic CMD, all of which should contain stars under a few 100 Myr in age. For the intermediate-age stars we select AGB stars brighter than and redder of the RGB, resulting in ages ranging between a few 100 Myr and a few Gyr. Finally, for the old population of stars we select RGB stars, which have ages in excess of 1 Gyr, although some AGB stars will also be found in the same region.

The actual regions used for the selection are shown in the CMDs in Fig. 1. The bottom right panel is a cartoon illustrating the selection of the MS/HeB, AGB, and RGB regions. The RGB region was selected using lines with slopes of 3.3 and 6.6 and F606W–F814W colors of 1.0 and 1.6 at the TRGB. The MS region was defined by adding all stars redder of $-0.5$ and blueward of a line with a slope of 3.3 and a color of 0.7 at the TRGB magnitude. Finally, the AGB region isolates stars $< 2$ mag brighter than the TRGB magnitude and redder of a line with a slope of 3.3 and a color of 1.2 at the TRGB magnitude. These boundaries were combined with the TRGB magnitude given in Table 1 and the completeness limits from Table 3 to determine the final regions for each galaxy shown in Figure 1. The regions were chosen somewhat conservatively; e.g., we chose to put space between the MS/HeB section and the RGB so that there would be little overlap between the two due to dust extinction or large photometric errors at faint magnitudes. From here on we refer to the stars in these CMD boxes as the MS, AGB, and RGB stellar populations.

4.1.1. Synthetic CMDs

To determine the typical ages of stars detected in our CMD boxes and to facilitate quantitative comparisons between galaxies and their different stellar populations, we generated synthetic CMDs using the MATCH program (Dolphin 2002) and the IAC-STAR program\(^3\) (Aparicio & Gallart 2004), using isochrones of Bertelli et al. (1994) and Girardi et al. (2000) in both cases. The synthetic stars were generated assuming a constant star formation rate (SFR) from 13 Gyr ago to the present and a metallicity that steadily increased from $[\text{Fe/H}] = -1.7$ to $-0.4$ (Garnett 2002). We used slightly different initial mass functions (IMFs) in the two CMDs. For the MATCH CMD a pure Salpeter IMF ($\alpha = 2.35$) was assumed between 0.1 and $120 M_\odot$, whereas in the IAC-STAR CMD we used the default Kroupa et al. (1993) IMF, which is steeper at the high-mass end ($\alpha = 2.70$).

To compare these CMDs with our observations, the synthetic stars were first transformed from Johnson $V$ and $I$ magnitudes to VEGAmag F606W and F814W colors. Then we mimicked observations of each galaxy as follows: First, each star was randomly assigned a surface brightness value based on the values of detected stars in each frame. Then, using the artificial star tests, we determined the chance that each star would be detected and the magnitude error based on the star’s initial F606W and F814W magnitudes (assuming the distance moduli shown in Table 1) and the surface brightness value. A final CMD was then made by randomly determining whether each star was detected and applying the determined errors. The resulting CMDs looked qualitatively similar to our observed CMDs, with the most notable difference being an offset of the AGB stars to somewhat brighter magnitudes in both synthetic CMDs relative to the real data and a deficit of MS/HeB stars in the IAC-STAR CMDs relative to the MATCH and the real galaxy CMDs. This could indicate either that the galaxies have had enhanced recent star formation or that their IMFs are not as steep as the Kroupa et al. (1993) IMF on the high-mass end.

Figure 4 shows the resulting age distribution of the MS, AGB, and RGB boxes in NGC 4144 using the MATCH and IAC-STAR synthetic CMDs. The age distributions for other galaxies are similar. This figure clearly demonstrates that we are separating the stars into young, intermediate-age, and old populations with our chosen CMD boxes. However, the separation is not perfect. Each bin has significant overlaps with the others due to unavoidable photometric errors and to true overlap in the colors and magnitudes of stellar populations with different ages. The IAC-STAR CMDs have age distributions similar to the MATCH CMDs but with the AGB populations weighted more toward older ages and a more significant contamination of old stars in the MS box (probably due to the relative lack of MS stars in the IAC-STAR models). Both effects likely result from the steeper IMF assumed for the Aparicio CMD. In the following sections of the paper, we use the MATCH CMD for comparisons with observations because it more closely reproduces the ratio of young MS and HeB stars relative to the number of older stars.

We note that these synthetic CMDs assume a constant SFR and thus are not useful in determining true star formation histories (SFHs). However, we are able to use them to get a sense of relative SFHs as a function of scale height and to get a rough sense of the ages of the stars in our CMD regions.

4.2. Stellar Density Profiles

Now we compare the surface density profiles of the MS, AGB, and RGB stars to examine possible variations in stellar population with disk height. Figure 5 shows the completeness-corrected profiles as a function of disk height for each field. Each profile is derived using the same methodology as in § 3, typically using $\sim 10,000$ stars per field. The surface densities are then normalized to have $\int \Sigma dz = 1$. All the fields show a similar pattern. The MS (solid line) stars have the narrowest distribution, while the AGB (dotted line) and RGB (dashed line) stars have broader distributions and typically show a dip near the midplane. Because we have corrected for incompleteness, the dip is almost certainly

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\(^3\) This work has made use of the IAC-STAR synthetic CMD computation code. IAC-STAR is supported and maintained by the computer division of the IAC.
Fig. 4.—Histogram of ages detected in defined CMD boxes (see Fig. 1) for NGC 4144 assuming a constant SFR from 13 Gyr to the present. Histograms are based on synthesized CMDs created with the MATCH (left) and IAC-STAR (right) programs as described in § 4.1. These plots show that stars in the MS box (solid lines) are dominated by stars ~100 Myr in age, while the AGB (dotted lines) and RGB (dashed lines) boxes have typical ages of ~1 and ~10 Gyr, respectively. Similar plots for other galaxies are qualitatively similar. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 5.—Normalized surface density as a function of scale height for young MS (solid lines), intermediate-age AGB (dotted lines), and old RGB (dashed lines) stars. Each surface density distribution is normalized to integrate to 1. Note that in all cases the MS distribution is the most peaked, while the RGB distribution is the widest. [See the electronic edition of the Journal for a color version of this figure.]
due to dust absorption, as we demonstrate in § 4.4 with a very simple model.

Figure 5 suggests that older stellar populations become more prominent with increasing disk height. We quantify this trend in Figure 6, which shows the ratios of surface densities in our different age bins. The ratios were normalized to those expected for a constant SFR using the MATCH synthetic CMDs (see § 4.1.1). A ratio of 1 in Figure 6 therefore corresponds to a constant SFR, and increasing values correspond to older stellar populations. We note that the ratio is only plotted where the signal-to-noise ratio is $> 3$. The small number of MS stars at large scale heights limits our ability to trace the $\Sigma_{\text{RGB}}/\Sigma_{\text{MS}}$ and $\Sigma_{\text{AGB}}/\Sigma_{\text{MS}}$ as high above the midplane as the profiles shown in Figures 3, 5, and 7. Also, NGC 4631 and NGC 4631-DISK are not included in Figure 6 because the high completeness limit results in very few RGB stars (see Fig. 1) and an increased contamination of AGB stars in the RGB box.

The top and middle panels of Figure 6 show that in each of the fields, RGB stars become more numerous relative to MS and AGB stars with increasing disk height. However, this trend shows an enormous variation from galaxy to galaxy. In IC 5052 the ratio $\Sigma_{\text{RGB}}/\Sigma_{\text{MS}}$ becomes as high as $\sim 100$ times the midplane value, while in NGC 55 and NGC 4244 the increase is much more moderate, to $\leq 10$ times the midplane value. This variation is most likely the result of a range of recent SFRs in our galaxies. The ratio $\Sigma_{\text{RGB}}/\Sigma_{\text{AGB}}$ is much more consistent from galaxy to galaxy, however. This may result from the overlapping time range spanned by stars in the AGB and RGB boxes and/or the large time ranges these boxes span relative to the MS. We argue in § 5 that the RGB population is likely to be dominated by truly old stars, much older than the AGB population. Interestingly, the field showing the flattest $\Sigma_{\text{RGB}}/\Sigma_{\text{AGB}}$ profile was the NGC 55-DISK field located in the outer parts of the NGC 55 disk, perhaps suggesting a different star formation or dynamical history at large radii ($\sim 5h_r$). However, this galaxy is the least inclined in our sample and is somewhat irregular in shape; therefore, results for this one system should not be overinterpreted.

The low values of $\Sigma_{\text{AGB}}/\Sigma_{\text{MS}}$ and the high values of $\Sigma_{\text{RGB}}/\Sigma_{\text{AGB}}$ result from a lack of AGB stars compared to the constant SFR MATCH synthetic CMD. This would seem to suggest that the galaxies’ SFHs are depressed at intermediate ages and enhanced at young ages. However, as we noted in § 4.1, the AGB morphologies in the synthetic CMDs are not well matched to the observational CMDs, probably because of the difficulty in modeling the AGB phase of evolution (Marigo 2001). This discrepancy combined with the differences seen between the two sets of synthetic CMDs suggests that a derivation of accurate SFHs using just the brightest stars in a galaxy is not yet possible.

To check whether the scatter in the $\Sigma_{\text{RGB}}/\Sigma_{\text{MS}}$ ratio was in part due to the varying radial coverages of the galaxies (Table 3), we remade the plots in Figure 6 using only stars within the central scale length of each galaxy. These plots were similar to those shown and showed comparable scatter. This suggests that the observed variations from galaxy to galaxy in the stellar population ratios reflect global differences in the galaxies’ SFHs and/or vertical structure. For instance, if we assume the trend toward older populations with increasing scale height results from disk heating, then the scatter in Figure 6 suggests substantial variations between galaxies in either the mechanisms that heated the disk or the SFH of the disk. Despite these variations, Figure 6 gives strong evidence that overall the age of the stellar populations increases with increasing scale height.

4.2.1. Stellar Population Scale Heights

To further quantify the differences in the vertical distribution of the three CMD regions, we fitted each surface density profile with a sech$^2$ function in which the normalization, central position, scale height ($z_0$), and background level were all allowed to vary. We fitted each profile only at disk heights $> z_{1/2}$ to avoid the dips near the midplane, except in IC 5052 and NGC 5023, for which we used disk heights $> 1.5z_{1/2}$ to allow fitting of the very narrow $\Sigma_{\text{MS}}$ profiles. Figure 7 shows the resulting fits to the $\Sigma_{\text{MS}}$, $\Sigma_{\text{AGB}}$, and $\Sigma_{\text{RGB}}$ profile of each galaxy in the top, middle, and bottom panels, respectively. The observed profiles are shown as a solid line, while the best-fitting sech$^2$ function is shown as a dashed line. The dotted lines at $\pm 3z_{1/2}$ (±1.5z_{1/2} in IC 5052 and NGC 5023) delineate the region excluded from the fit. The error bars on the data points are used to weight the sech$^2$ fits and reflect Poisson errors in the number counts but do not include uncertainties in the completeness corrections. The scale height of the best-fitting sech$^2$ function is shown in the upper left corner of each panel, and the error shown is scaled by the square root of the reduced $\chi^2$ of the fit. The reduced $\chi^2$-values for a majority of the fits were between 0.8 and 1.3 but were larger for NGC 55 and

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NGC 4631 due to their irregular structure. Scale heights and errors for all the fits are shown in Table 4.

We find that in each galaxy, the MS scale height value is the narrowest, followed by the AGB and then the RGB. In all cases the RGB population is significantly broader than the AGB, MS, and $K_s$-band $z_0$-values. This result strongly suggests the presence of an older component with a larger scale height. An analysis of the variations in scale height of the MS, AGB, and RGB populations with scale length in each of the galaxies turned up no obvious trends. We also identified no trends with galaxy rotation speed, due to the small range of masses spanned by our sample galaxies. We note that in some cases, the $z_0$ derived for all stars ($\S$ 3) is somewhat larger than the $z_0$ derived for just the RGB stars.

This results from the lower scale heights used in the fits to the different stellar populations; if the lower limit for the fit to all stars is reduced from $5z_{1/2}$ to $3z_{1/2}$, the derived $z_0$ is less than or equal to the RGB star $z_0$ in each galaxy, as expected if the total stellar density is well characterized by a combination of the MS, AGB, and RGB components. The fits presented here for these different stellar population components are in general not extremely sensitive to the range of $z$-values used. Varying the lower limit of the fit between $1.5z_{1/2}$ and $5z_{1/2}$ typically changed the AGB and

Fig. 7.—Model fits to the observed surface density distribution as a function of disk height in each galaxy for the MS (upper plots), AGB (middle plots), and RGB (lower plots). The dashed line shows the best-fitting sech$^2$ model excluding data with $|z/z_{1/2}| < 3$ (dotted lines), while the vertical dotted lines show the range of $z$-values excluded from the fit. The numbers in the upper left corners give the scale height of the best-fitting sech$^2$ function.
RGB $z_0$-values by <10%. The compact MS components were more dramatically affected because of the smaller number of stars at large scale heights.

From this analysis it appears that NGC 4631 has the "thickest" old component, with an RGB scale height of $\sim$1250 pc, roughly 2.5 times larger than the MS and $K_s$-band fits. We note that the fits for NGC 4631 were truncated at large negative disk heights to prevent the contamination of stars from companion galaxy NGC 4627. IC 5052 and NGC 4144 have similar ratios (2.5) of RGB to MS scale heights, while NGC 4244 has the smallest ratio, with an RGB scale height only 1.7 times that of the MS stars.

There is also evidence for a modest flaring of the stellar components between the central and DISK pointings of NGC 55 and NGC 4631. The DISK fields are centered 4.8 and 6.1 scale lengths (see Table 2) from the center of NGC 55 and NGC 4631, respectively. An increase in $z_0$-values by a factor of 1.1–1.6 is seen for all three components in NGC 55 and for the AGB and RGB components in NGC 4631.

The profiles deviate from the fitted sech$^2$ profile significantly near the midplane. This deviation is almost certainly due to dust; we model this effect in §4.4. At larger disk heights (>2–3 kpc) there is also a slight overdensity in the RGB components of IC 5052, NGC 4144, NGC 4244, and NGC 5023. These overdensities hint at the possible presence of an even more broadly distributed old component. In three of these galaxies, the RGB fits had elevated $\chi^2$-values relative to the MS and AGB fits. We estimate that these overdensities occur at a surface brightness $\mu_{606W} \approx 28$ mag arcsec$^{-2}$, assuming a luminosity function similar to...
Galactic globular clusters (Buonanno et al. 1994; Kravtsov et al. 1997). However, without better knowledge of the background level, it is not possible to verify the existence of this component.

The scale heights measured in the $K_s$ band (Table 4) are closest to those measured for the MS and AGB components. Half of the galaxies have $K_s$-band scale heights closer to the MS value, and the other half closer to the AGB value. This suggests that the $K_s$-band light in these galaxies is dominated by relatively young stellar populations, probably red supergiants and AGB stars (in agreement with the findings of Aoki et al. [1991]). This result runs contrary to the common assumption that the near-IR light primarily traces older stellar populations (e.g., Florido et al. 2001) and is significant in that near-IR luminosity is often used as a proxy for stellar mass when comparing galaxies of different types and masses. However, we note that our $K_s$-band scale heights are biased toward higher surface brightness populations due to the bright limiting isophote of the 2MASS data from which they are derived.

4.2.2. Comparison to Previous Observations

The results above indicate that there is a systematic increase in the vertical scale heights of older stellar populations in our sample of low-mass, late-type disks. Before investigating possible origins for these structural differences in §§ 4.3 and 5, we now compare our measurements of scale heights with previous observations of the vertical structure of disks.

The most detailed constraints on the scale heights of different stellar populations come from the solar circle of the Milky Way. Studies have revealed a complicated disk structure, with young and old thin disks embedded within a more extended thick disk. The young thin disk is the narrowest of the three, having a scale height of $z_0 \sim 200$ pc, as traced by stars with bright absolute magnitudes ($M_V \leq 3$) (Schmidt 1963). In contrast, the scale heights of the young MS stars in our sample are almost all significantly larger than the Milky Way value, suggesting that the low-mass galaxies in our sample form stars in a layer thicker than that in the Milky Way, consistent with Dalcanton et al. (2004). The resulting axial ratios for our samples’ young star-forming disks are also much thicker as well, with $z_0/h_0 = 1.8-6.3$ (see Table 4) for our sample galaxies versus $z_0/h_0 \sim 15$ for the young thin disk of the Milky Way.

The division of the Milky Way’s older stellar populations into a thin and thick disk was first introduced by Gilmore & Reid (1983) to explain a break in the number counts of F and G stars at $\sim 1$ kpc. While the need for two old disk components was long debated, recent observations of systematic $\alpha$-element enhancement in thick-disk stars (most recently, Gratton et al. 2003; Feltzing et al. 2003; Mishenina et al. 2004; Bensby et al. 2005) strongly suggest that the thick disk is indeed distinct from the old thin disk. Recent observations (Chen et al. 2001; Siegel et al. 2002) give a scale height for the old thin disk of $z_0 \sim 600$ pc, similar to that found in the original Gilmore & Reid (1983) study. These same studies suggest that the exponential scale height of the thick disk is $h_0 \sim 700$ pc (corresponding to $z_0 \sim 1400$ pc, thinner than originally claimed). The Milky Way thick disk is therefore roughly twice the height of the old thin disk and 7 times the height of the young thin disk.

Within our own sample, the scale heights of the old RGB components are mostly intermediate between that of the Milky Way old thin disk and the thick disk. Our sample galaxies have much lower masses and surface densities than the Milky Way, and, lacking any firm model that predicts how the properties of the old thin disk and the thick disk should vary with galaxy mass, we are hesitant to attribute the extraplanar population to either an old thin or a thick disk on the basis of the surface brightness profiles alone. There are no dramatic inflection points in the RGB surface density profiles plotted in Figure 7 that would assist in a unique separation of old thin-disk and thick-disk stars, and the possible overdensity of stars above 2–3 kpc may well be due to a stellar halo. Even if the RGB component is similar to the Milky Way thick disk, this lack of inflection is not unexpected. In the Milky Way, the inflection point in the surface density of F and G dwarf stars that marks the separation of the thin and thick disks is likely the result of two different populations of stars separated in age. The lack of similar inflection points in our RGB profiles can easily be explained if the RGB stars do not have as wide a range of ages as the Milky Way dwarves. We show in § 5 that the RGB stars in our galaxies may very well be dominated by a single-age population.

We do note, however, that the axial ratios of the RGB disks range over $h_0/z_0 = 1.0-3.3$, with a median of 1.8 (adopting the $K_s$-band radial scale length and averaging the two independent measurements for NGC 55 and NGC 4631). For comparison, the axial ratios of the old thin and the thick disks of the Milky Way are 5.0 and 2.1, respectively (assuming $h_0 = 3$ kpc for both components). Thus, in terms of their overall structure, the RGB components we detect are significantly more round than the Milky Way’s old thin disk and are distributed more like the Milky Way thick disk. However, without additional information we cannot ascribe a common formation scenario to our observed RGB components and the Milky Way thick disk. We revisit this issue in the discussion (§ 6), after analyzing the disk heating and the vertical metallicity gradients of our sample galaxies.

Outside of the Milky Way, the most detailed information comes from studies of the vertical distribution of resolved stars in HST images, similar to the work we present in this paper. Tikhonov et al. (2005) and Tikhonov & Galazutdinova (2005) present evidence for extended components in six galaxies, which they qualitatively argue correspond to thick disks and halos. Of the galaxies that overlap our sample (NGC 55, NGC 4144, and NGC 4244), they include archival WFPC2 observations to reach greater disk heights in NGC 4244 and NGC 55 than spanned by our ACS images. In both cases they assume a priori that the RGB stars at lower disk heights trace a thick disk. For NGC 4244, Tikhonov & Galazutdinova (2005) show an exponential distribution of RGB stars between $\sim 1$ and 3 kpc (their Fig. 8) that appears to roughly match the scale height of the profile shown in Figure 7. Beyond 3 kpc, they see a flattening in the number counts that they claim indicates a halo, but that may also be the background level. For NGC 55, Tikhonov et al. (2005) plot an exponential distribution of RGB stars between 2 and 7 kpc, i.e., at much greater disk heights than probed by our data. However, based on inspection of their Figure 12, the extended RGB component has a $z_0$-value of $\sim 2$ kpc, which is 2–3 times the width of the RGB component we fit. Although they assume this component is due to a thick disk based on its exponential surface density distribution, the axial ratio of this component would in fact be prolate ($h_0/z_0 \sim 0.5$) and thus may be more analogous to the Milky Way’s stellar halo. The change in slope also implies a break in the RGB distribution in NGC 55 at around 2 kpc. By analogy, this may indicate that the marginal overdensities we are seeing at comparably large disk heights in our RGB profiles might be the signature of an additional broader halo component. Mould (2005) also finds the presence of old stars at large scale heights, and while these stars are automatically assumed to be a...
thick-disk component, no detailed analysis of their spatial distribution is presented.

In addition to these recent studies of resolved stars, most previous studies of the vertical structure of disks have focused on detecting thick disks and stellar halos using unresolved surface brightness profiles of the galaxies (e.g., Pohlen et al. 2004; Fry et al. 1999; Dalcanton & Bernstein 2002; Neeser et al. 2002). Because we only detect stars at bright magnitudes, it is difficult to accurately convert our measured surface density of stars (Fig. 2) to a surface brightness. However, assuming the outer parts of our galaxies have luminosity functions similar to Galactic globular clusters (Buonanno et al. 1994; Kravtsov et al. 1997), we estimate that we reach F606W surface brightnesses of $\sim 26$ mag arcsec$^{-2}$. This is comparable to the depth reached in deep, ground-based observations.

Only one of our galaxies has been analyzed for vertically extended components using ground-based data. Fry et al. (1999) present R-band surface photometry of NGC 4244 and find no evidence of a second thick-disk component, based on the lack of an inflection point in the surface brightness distribution above the plane. They trace the vertical profile of NGC 4244 along the minor axis to $\sim 2$ kpc, at which point it falls below their surface brightness limit of 27.5 mag arcsec$^{-2}$. We trace the RGB component out to nearly 3 kpc and find a scale height that is similar to their fitted R-band scale height (assuming $h_z = \frac{1}{2} z_0$). Their lack of an inflection in the surface brightness distribution does not unambiguously rule out the presence of multiple components.

The ubiquity of thick disks in galaxies has previously been proposed by Dalcanton & Bernstein (2002) based on color gradients in edge-on disk galaxies. Our observations confirm that the color gradients (at least at the low-mass end) are the result of true differences in stellar populations. However, whether these gradients have a formation mechanism analogous to that of the Milky Way thick disk is not clear.

One set of observations that reaches considerably deeper than these ground-based observations is presented by Zibetti et al. (2004), who used stacked Sloan images to show that halos are common in late-type, edge-on galaxies. Their composite galaxy has a significantly wider field of view and poorer resolution than our observations. They show that the best-fitting model to their data is a disk + halo model, with the disk component dominating out to roughly 10 exponential scale heights ($\sim 10 z_{1/2}$). Their limited resolution and combination of a heterogeneous sample of galaxies would likely prevent them from seeing the RGB components we see in our galaxies. However, the possible detection of the more extended RGB components in IC 5052, NGC 4144, and NGC 5023 may be halos similar to the Zibetti et al. (2004) halo.

4.3. Disk Heating

The increase in $z_0$ seen in each galaxy between the MS, AGB, and RGB populations (Fig. 7, Table 4) could result from a number of mechanisms, including vertical heating of a thin disk. Such a model would naturally produce the observed trend of older stellar populations having larger scale heights. In Figure 8 we
plot the increase in scale height with mean stellar age for four fields that span the observed behavior in our sample. We plot scale heights for the RGB and AGB, normalized by the MS scale heights, with the height of the symbols indicating the 1σ uncertainties for $z_0$. Note that when interpreting our data in the context of disk-heating models we are therefore implicitly assuming that the RGB and AGB stars were originally formed in a layer with a scale height comparable to that of the present-day MS stars. We assign characteristic ages to the RGB and AGB using the MATCH synthetic CMD tests for a constant SFR (§ 4.1.1). However, because the galaxies’ actual SFHs may differ significantly from the constant SFR assumed in Figure 4, we cannot assign a single age to each stellar population. Instead, we use the resulting age distributions to identify the 25th, 50th (median), and 75th percentile ages. The resulting age ranges are shown by the width of the individual boxes in Figure 8. However, note that the actual age of the population may lie entirely outside of the boxes, for example, if the RGB stars were all formed in a single burst 12 Gyr ago. Thus, when interpreting Figure 8, one has substantial allowance in assigning an age.

Overplotted on Figure 8 are dashed lines showing a range of power-law increases in the disk scale height $z_0$ with time ($z_0 \propto t^{-\alpha}$). For an isothermal sech² profile, the $z_0$-values are related to the vertical velocity dispersion ($\sigma_z$):

$$z_0 = \frac{\sigma_z^2}{2\pi G \Sigma},$$

where $\Sigma$ is the surface density of the disk (eq. [17] in van der Kruit 1988). Studies of disk heating traditionally use power laws in the velocity dispersion, $\sigma_z \propto t^{-\alpha}$, and thus, $\alpha = \beta/2$. Figure 8 therefore demonstrates that the vertical velocity dispersions of our galaxies have increased no faster than $\alpha = 0.15$. More specifically, there are no characteristic ages that can be assigned to the AGB and RGB stars that yield heating rates greater than $\alpha = 0.15$ (with the possible exception of the more massive, interacting galaxy NGC 4631), and thus, this conclusion is robust even in light of our substantial age uncertainties.

In contrast, the disk heating that has been observed in the Milky Way is comparatively rapid. The age-velocity dispersion relation for Milky Way disk stars suggests that the vertical velocity dispersion increases with time, with values of $\alpha$ ranging between 0.3 and 0.6 (e.g., Wielen 1977; Binney et al. 2000; Nordström et al. 2004; see the summary in Table 1 of Hänninen & Flynn 2002). In contrast, our limit of $\alpha \leq 0.15$ is significantly smaller than the Milky Way value. These data immediately suggest that any disk heating in our low-mass galaxies has been far less effective than in the Milky Way. Moreover, if some fraction of the extraplanar RGB stars are not due to disk heating and are instead due to direct accretion or in situ formation at large scale heights, or if the RGB stars are weighted toward old ages (as we argue below in § 5), then the actual rate of disk heating is even lower than suggested by Figure 8.

There are several reasons why disk heating is expected to be low for our sample galaxies. Within the Milky Way, the increase in vertical velocity dispersion with time is thought to be due to scattering by spiral arms (Barbanis & Woltjer 1967; Sellwood & Carlberg 1984; Carlberg & Sellwood 1985), by molecular clouds (Spitzer & Schwarzschild 1951), or by both (Carlberg 1987; Jenkins & Binney 1990; Jenkins 1992; Shapiro et al. 2003; see also the review by Lacey 1991). However, our galaxies have sufficiently low masses and surface densities that they are unlikely to be globally gravitationally unstable (Dalcanton et al. 2004; Verde et al. 2002) and thus would not host strong spiral arms. Given that scattering by spiral arms seems to be the dominant heating mechanism in the Milky Way (e.g., most recently, De Simone et al. 2004), the absence of spiral arms alone should cause a drastic drop in heating rate down to $\alpha \sim 0.2-0.25$, the expected value for heating by giant molecular clouds alone (e.g., Hänninen & Flynn 2002). Likewise, the absence of strong dust lanes in these systems and the results of § 4.4 both indicate that the cold molecular interstellar medium (ISM) is in a thicker layer than in the Milky Way. This large scale height for the cold ISM and the general lack of molecular gas in low-mass galaxies (Young & Scoville 1991; Leroy et al. 2005) should therefore further suppress the efficiency of disk heating. Finally, the young stellar disks in our sample are apparently much thicker than in the Milky Way, which could reduce the efficiency of any heating mechanism (Freeman 1991). Shapiro et al. (2003) also argue for reduced disk heating in late-type galaxies based on the ratio of vertical to radial velocity dispersions. However, their rationale for the observed trend is opposite from what we conclude from our data.

As an aside, the low observed heating rates may provide strong constraints on cosmologically important sources of disk heating, including late-time satellite accretion (Quinn et al. 1993), massive black holes (Lacey & Ostriker 1985), or halo substructure (e.g., Hänninen & Flynn 2002; Benson et al. 2004). However, the expected heating rates for such models have been calibrated for massive spiral disks, not the thicker, lower surface density galaxies studied here.

### 4.4. Modeling Dust Effects on the Stellar Density Profiles

Before continuing to explore the origin of extraplanar stars, we briefly examine the vertical distribution of the dust layer. At first glance, interpretation of the stellar density profiles near the midplane in Figure 5 might be somewhat confusing. If the dips in surface density are due to dust, why does the dust appear to affect the RGB and AGB stars more than the MS stars? We suggest this may occur because the dust layer is opaque near the midplane and is distributed with a scale height greater than or equal to that of the MS population but less than that of the AGB/RGB populations. The MS stars we are seeing would then lie entirely in front of an obscuring dust screen, while the AGB/RGB populations would have a significant population at large disk heights above which the galaxy becomes optically thin. The dip in their numbers near the midplane is then explained because the optically thick dust layer obscures some fraction of the stars along the line of sight.

To test this explanation, we built a simple “toy model” galaxy with MS, RGB, and AGB populations distributed as sech² profiles with $z_0$ as shown in Table 4. All components were given identical radial distributions with the $K_s$-band exponential scale length. The dust component was assumed to also follow a sech² profile with a variable scale height, $z_0,dust$, and a radial distribution identical to that of the stars. For simplicity we assumed that the dust has no effect at an optical depth less than 1 but is completely obscuring at greater optical depths. Thus, along a line of sight the dust is completely transparent to $\tau = 1$ and completely opaque beyond. For each vertical position we integrated the dust component along the line of sight until an optical depth of 1 was reached, which set the depth of the dust screen at that height. Stellar density profiles for the three separate populations were then created by totaling the number of stars in front of the dust screen at each height. We then normalized the stellar density profiles as in Figure 5.

Figure 9 shows the resulting model of NGC 4144 for three values of $z_0,dust$ presented for comparison to the observations.
shown in Figure 5. In each case the amount of dust in the midplane is the same. The underlying values for $z_0$ were adopted from Table 4 (374, 699, and 934 pc for the MS, AGB, and RGB, respectively). The left panel shows the results for a dust layer whose scale height is narrower than all three stellar components. For this case, there is a pronounced dip in the surface density profile of all three components. In the middle panel, the value of $z_{0,dust}$ is between the $z_0$-values for the MS and the AGB/RGB populations. In this case there is a dip only in the AGB/RGB, because the height of the MS layer is entirely confined within the opaque dust layer, allowing only the unobscured stars on the near side of the galaxy to be detected. The right panel has a dust layer larger than both the MS and AGB value, and therefore, a dip is seen only in the RGB component. The middle panel does a good job of qualitatively matching the observations for NGC 4144 in Figure 5.

Referring back to Figure 5, we can see that the MS profile lacks a dip near the midplane for most of the fields, while the RGB has a dip in all cases within $(2-3)z_{1/2}$. This suggests that the dust in the galaxy is opaque below $(2-3)z_{1/2}$ and that it is distributed in a layer with thickness greater than or equal to that of the MS stars. Because the MS stars are already distributed in a thicker distribution than in the Milky Way, this result supports the Dalcanton et al. (2004) finding that galaxies with circular velocities below 120 km s$^{-1}$ (C0) have large dust scale heights and do not form thin dust lanes. All the galaxies presented here except NGC 4631 are below this circular velocity limit (Table 1).

This model also suggests that although the depth to which we see in each galaxy is different at differing scale heights, it is the same for all the stellar populations at a single scale height. This validates the comparisons made in Figure 6 between the ages of the stellar populations at different scale heights.

Although this model matches the gross characteristics of many of the profiles shown in Figure 5, it fails to fully explain their details. Most notably, in NGC 55 and NGC 4244, the MS profiles are significantly lower than the best-fitting sech$^2$ function, contradicting the idea that all the stars we are seeing lie in front of a screen. This is likely the result of our model’s lack of sophistication. Physically, it does not take into account the possibility of flares or changing scale lengths as a function of stellar population. In addition, it treats dust extinction in a very simplistic fashion. A more sophisticated treatment of the dust (such as the one presented by Matthews & Wood [2001]) is beyond the scope of this paper. The conclusions reached in this section should be considered tentative and will be tested in a later paper, in which we will present a more realistic dust model.

5. METALLICITY DISTRIBUTION FUNCTIONS

As has been shown previously (e.g., Da Costa & Armandroff 1990; Armandroff et al. 1993; Fryxel & Gilmore 2002), the color of the TRGB can be used to constrain the metallicity of old stellar populations. Although reddening due to dust will prevent an accurate measurement of the metallicity of stars near the midplane, we can determine a rough metallicity for stars above the midplane, where the effect of dust and the contamination from AGB stars are small (as shown in Fig. 6, middle).

Figure 10 shows a composite CMD of all high-latitude stars (above $4z_{1/2}$) in IC 5052, NGC 55, NGC 55-DISK, NGC 4144, NGC 4244, and NGC 5023. This disk height limit was chosen...
(1) to be well above any of the dips associated with dust in Figure 5, (2) to dramatically reduce contamination by AGB and HeB stars that might interfere in the metallicity determination, and (3) to be where thick-disk stars dominate in the Milky Way (Chen et al. 2001). Overlaid on the CMD are 10 Gyr old RGB isochrones (Girardi et al. 2000) at metallicities ranging from $[\text{Fe/H}] = -2.3$ to 0.0, with higher metallicities being redder. Examination of Figure 10 shows that the peak of the distribution falls to the left of the $[\text{Fe/H}] = -1.3$ and $-0.7$ lines. Roughly 13% of the stars fall blueward of the $[\text{Fe/H}] = -2.3$ isochrone, probably due to a combination of photometric error and the presence of AGB stars. Very few are redder than the $[\text{Fe/H}] = -0.4$ isochrone. Overall, Figure 10 indicates that most of the stars above $4\sigma_{1/2}$ are moderately metal-poor.

Improving on the metallicity determinations in Paper I, here we derive MDFs using untransformed magnitudes and Padua isochrones (Girardi et al. 2000). To determine MDFs for individual galaxies, we binned the stars in up to three independent magnitude bins that were above the 20% completeness limit. We estimated the errors as a function of metallicity by inserting stars of a specific metallicity/color, giving them appropriate color errors, and then determining the spread in the resulting metallicity distribution. This procedure gave errors of 0.5–0.8 dex at $[\text{Fe/H}] = -2.3$. However, the shapes of the distributions are much more believable on the metal-rich end, where the isochrones are well separated, giving errors of $<0.1$ dex at $[\text{Fe/H}] = -0.4$. At the peak of the MDF ($[\text{Fe/H}] = -0.9$), typical errors are 0.2 dex, suggesting that the peak metallicities derived here are fairly reliable.

Comparing the peak metallicity of the extraplanar stars to known Milky Way populations, Figure 11 indicates that the metallicities of the extraplanar stars are a factor of 10 too high to be analogs of the Milky Way’s stellar halo. However, the shapes of the distributions are much more believable on the metal-rich end, where the isochrones are well separated, giving errors of $<0.1$ dex at $[\text{Fe/H}] = -0.4$. At the peak of the MDF ($[\text{Fe/H}] = -0.9$), typical errors are 0.2 dex, suggesting that the peak metallicities derived here are fairly reliable.

Comparing the peak metallicity of the extraplanar stars to known Milky Way populations, Figure 11 indicates that the metallicities of the extraplanar stars are a factor of 10 too high to be analogs of the Milky Way’s stellar halo ($[\text{Fe/H}] = -1.7$; Wyse & Gilmore 1995). This result would not change even if all the stars blueward of the $[\text{Fe/H}] = -2.3$ isochrone were low-metallicity RGB stars. We note, however, that the low metallicity of the Milky Way halo may not be typical. The halo of Andromeda has been found to be much more metal-rich than in the Milky Way, with a peak $[\text{Fe/H}] = -0.6$ (Holland et al. 1996; Brown et al. 2003), although there is difficulty ascribing these outer stars to a halo population per se, given M31’s complicated outer structure (Ferguson et al. 2002).

Of all the Milky Way components, we find that the peak metallicities are most consistent with those of the metallicity of the Milky Way thick disk, which has $[\text{Fe/H}] = -0.8$ based on F/G dwarfs (Wyse & Gilmore 1995). The extraplanar stars studied here are somewhat more metal-poor than the Milky Way’s thick disk (by up to 0.3 dex). However, this offset may not be surprising, given the lower mass of our galaxy sample ($V_c \sim 80$ km s$^{-1}$ vs. $V_c \sim 220$ km s$^{-1}$ for the Milky Way).

As in the Milky Way (Wyse & Gilmore 1995; Haywood 2001), the extraplanar stars appear to be more metal-poor than the thin, young, MS population. Although dust prevents us from reliably measuring the metallicity of stars near the midplane, we can estimate their metallicity using the current gas-phase metallicity. NGC 55, the only galaxy in our sample with a gas-phase abundance measurement, has 12 + log (O/H) = 8.32 at one disk scale length (Garnett 2002). This metallicity corresponds to...
[Fe/H] \sim -0.6 \) (assuming [Fe/O] = 0), which is 0.5 dex more metal-rich than the extraplanar stars at a comparable radius. Other late-type disks with similar rotational velocities from the Garnett (2002) compilation have comparable gas-phase metallicities, suggesting that the offset in metallicity between the midplane and the extraplanar populations is likely to be systematic. Although they do not explicitly examine stars as a function of scale height, studies of metallicities in other galaxies using methods similar to ours also find broad agreement with the presence of an extended [Fe/H] \sim -1 population of RGB stars. The LMC (which has a mass similar to those of the galaxies in our sample) has a peak metallicity distribution of [Fe/H] \sim -0.6 for RGB stars in the disk (Cole et al. 2000). Recent papers on the outer regions of M33 also find peak [Fe/H] values of -1.0 (Davidge 2003; Tiede et al. 2004). Furthermore, a recent paper by Davidge (2005) derives an [Fe/H] of roughly -1 for NGC 55 using near-IR photometry of resolved extraplanar stars, closely matching our peak metallicity in Figure 11. Our data and others therefore suggest the pervasive presence of a significant [Fe/H] \sim -1 old population in late-type galaxies. If our association of this population with a thicker disk is generally true in other galaxies, then it presents an attractive solution to the “G-dwarf” problem seen in the Milky Way by providing the necessary prompt initial enrichment for stars in the thin disk (Truran & Cameron 1971).

Overplotted on Figure 11 as dashed lines are the expected metallicity distributions for closed-box “simple” chemical evolution models (eq. [20] of Pagel 1997) scaled to the peaks of the MDFs. While the basic shapes of these models are similar to our MDFs, there appears to be a deficit in some galaxies of stars at both low and high metallicities. A deficit at high metallicities is expected if star formation truncates before all the gas is consumed. Within the context of thick disk formation models, this truncation may occur if some of the gas reservoir that forms the extraplanar stars instead settles into the thin disk, if the extraplanar stars were heated from a previously thin but gas-rich disk, or if the extraplanar stars were directly accreted from merging satellites that suffered from tidal stripping or supernova blowout. The apparent deficit of stars at low metallicities may be another manifestation of the widespread G-dwarf problem. Thus, while the existence of a substantial population of stars at [Fe/H] \sim -1 may help to solve the G-dwarf problem in the thin disk, it may have simply pushed the problem into a new component. The solution to the extraplanar G-dwarf problem will likely lie among the suite of popular models previously explored for the thin disk.
(see Pagel 1997). However, some of the deficit of stars at low metallicities may also result from the photometric errors and methods used to construct the MDFs, as discussed above.

Finally, we note that the peaks of the MDFs given in Table 5 are significantly more metal-rich than our previous determination presented in Paper I. Rather than using native F606W − F814W colors, these earlier measurements applied the metallicity-color relation of Lee et al. (1993) to the mean color of the giant branch transformed to the Johnson-Cousins filter system. These previous values, reproduced in Table 5, range from [Fe/H] of −1.2 to −1.7 versus −0.7 to −1.1 in the present work. We believe that in addition to the magnitude transformation, the difference in derived metallicity results in part from the difference in binning (in [Fe/H] vs. F606W − F814W), such that the mean color does not correspond to the peak metallicity. This offset can be seen in the 0.1–0.2 dex offset between the mean and peak metallicity in Table 5. Furthermore, the Paper I determination also included stars at somewhat lower disk heights, thereby increasing the number of AGB contaminants. We believe that the MDFs and their peak metallicities that we present here are more reliable than the estimates given in Paper I.

5.1. Vertical Metallicity and Color Gradients

Models for the origin of extraplanar stars (disk heating, direct accretion, etc.) predict different degrees of variation in the stellar metallicity with height above the plane. To investigate the vertical variation of metallicity with disk height z, we have examined the median color of the RGB stars as a function of the height above the midplane. Figure 12 shows the median color of RGB stars between $M_{F814W}$ of −3.2 and −3.6 and redward of F606W − F814W = 0.7, binned by the scale height of the galaxies. Data are plotted where errors in the median color are $<0.05$ mag. The hatched region at low disk heights shows where the effects of internal reddening may impact the colors of the stars. For the three fields with profiles extending beyond 2–3 kpc, we bin the RGB stars at large disk heights in a single bin to reach adequate signal-to-noise ratio in our measurement of the median color (Fig. 12, diamonds). We note that these are the same stars that comprise the possible extended components discussed in § 4.2.

Figure 12 demonstrates three main points. First, the color gradients in the galaxies are relatively small, indicating that the stars have nearly uniform metallicity with increasing distance above the plane, particularly at scale heights above the region potentially affected by dust. However, we note that the stars at very large radii (diamonds) do tend toward bluer colors, possibly indicating the presence of a more metal-poor population at $z \geq 10z_{1/2}$ (2–3 kpc). Second, the color gradients show no systematic trends and are likely to be rising or falling. Finally, all the galaxies have very similar RGB colors (as demonstrated already in Fig. 11).

Our metallicity gradient results are consistent with previous observations of these and other low-mass spiral galaxies (Davidge 2005; Tikhonov et al. 2005; Mould 2005). Mould (2005) used HST archival data to study the vertical properties of disks in four low-luminosity ($M_F \sim -16$), edge-on galaxies comparable to those studied here. Using AGB, RGB, and red supergiant stars over a large range of magnitudes ($-8.5 \leq M_V \leq -5$), he calculated the mean colors up to 2 kpc from the plane. His main results are that there are slight or no color gradients as a function of disk height and that the metallicities of the stars at disk heights between 400 and 2000 pc are between −0.8 and −1.0 in all four galaxies, in excellent agreement with what we find here. Tikhonov et al. (2005) also state that any metallicity gradient in NGC 55 is very small, in agreement with our observed lack of color gradients in Figure 12. Recent simulations of thick disks by Brook et al. (2005) also show a lack of any metallicity gradient with disk height.

The lack of strong metallicity gradients can be explained in a number of ways. Mould (2005) suggests the lack of metallicity gradients rules out dissipative and simple accretion models for thick-disk formation and favors a model in which thick disks form during interactions. We note that the lack of metallicity gradient may also be enhanced by an “age bias” in the metallicity measurements. The mass of stars on the RGB changes from $\sim 2 M_\odot$ at an age of 1 Gyr to $< 1 M_\odot$ at 10 Gyr. Given the steepness of the IMF in this mass range, the RGB age distribution will be weighted toward older ages and therefore to a more uniform metallicity. However, based on the constant SFR models in § 4.1, it still appears that the RGB stars could span a wide range of ages, even in the presence of the expected age bias. Therefore, the simplest interpretation of the lack of gradients in our data is that many of the RGB stars at disk heights above $4z_{1/2}$ ($\sim 1$ kpc) formed at a similar time and thus have comparable enrichment histories, eliminating any metallicity gradient. This scenario could be explained either by a sudden heating of the disk by interaction or by accretion of gas-rich satellites that results in the formation of a thick component. N-body simulations have shown that early merging and accretion events can produce thick disks with old ages (Abadi et al. 2003; Brook et al. 2004, 2005).

6. DISCUSSION AND CONCLUSIONS

The work presented here has identified a number of main observational results:

1. In low-mass, late-type galaxies the thickness of a stellar population increases systematically with the age of the stars being studied. This behavior has been seen not just in all six of the galaxies studied here but in all other HST studies of edge-on, late-type galaxies, and in the Milky Way as well. The larger scale heights of older stellar populations are therefore likely to be a generic property of galaxy disks.
2. All the studied galaxies show a clear intermediate-age (1–5 Gyr old) population whose scale height is intermediate between that of the young MS stars and the older red giants.

3. The dominant old stellar population has a metallicity [Fe/H] $\sim -1$ but shows little or no gradient between $z_{2/3}$ and $10z_{2/3}$ above the plane. Above this height ($\sim 2$–3 kpc), there are tentative indications of decreasing metallicities, which may be associated with slight overdensities in the RGB surface density at similar distances above the midplane.

4. In the low-mass galaxies studied here ($V_c \sim 70$–130 km s$^{-1}$), the young stellar population is systematically thicker than in the Milky Way and has a vertical scale height comparable to the thickness of the dust layer. This suggests that the cold ISM has a larger scale height in low-mass galaxies, consistent with the lack of dust lanes observed in such systems (Dalcanton et al. 2004).

5. The young and intermediate-age stellar populations dominate the integrated near-infrared light of late-type, low-mass galaxies.

We now interpret these observational facts in the context of disk formation models. First, taken at face value, the old RGB component's $\sim 3:1$ axial ratio and [Fe/H] $\sim -1$ metallicity suggest a close correspondence with the Milky Way's thick disk. However, each of our galaxies' scale heights steadily increase from the young MS to the intermediate-age AGB and the older RGB. The uniformity of this trend strongly suggests that our disks are not simply the superposition of two components (i.e., a thick and thin disk). Instead, the data require a more complex model incorporating some disk heating to explain the systematically larger scale height of the intermediate-age population. The necessary disk heating would also have affected any older population, and thus must make some contribution to the thicker population of RGB stars. The required amount of disk heating is much smaller than is seen in the Milky Way ($\sim 4.3$) and could likely be provided by molecular clouds or minor mergers. The latter scenario is slightly favored by the large variations in the apparent change of disk scale height with time (Figs. 6 and 8). Heating through satellite accretion and interaction could naturally produce these stochastic variations. However, numerical simulations of heating in diffuse, low-mass disks would be required to definitively constrain any of the above scenarios and to assess how significant a contribution heating may have made to the thicker RGB component.

While the above argument strongly suggests that disk heating must play some role in the production of the extraplanar stars, the lack of a metallicity gradient in RGB stars at moderate disk heights (500–2000 pc, as shown here and in Mould [2005]) suggests that steady disk heating cannot entirely explain the thickest component of old RGB stars. If the past SFR has been constant, then there is a significant overlap between the stellar ages of the AGB and RGB regions of the CMD (Fig. 4). A significant fraction of the RGB stars should therefore have smaller scale heights, younger ages, and enriched metallicities and would thus produce a steady increase in metallicity toward the midplane for all but the most contrived scenarios. The most attractive explanation for the lack of metallicity gradient is that instead of there being a constant SFR, the majority of RGB stars at all scale heights must have formed early and with a well-mixed metallicity distribution. Such a population would dwarf any subsequent population of enriched RGB stars with lower scale heights. While steady dynamical heating could push this ancient population to larger scale heights, it could not simultaneously account for the recent dynamical observations of counterrotating disks at these disk heights in comparable galaxies (Yoachim & Dalcanton 2005). Taken together, these observations are better explained by scenarios involving the formation of a thick disk of stars in merger events (as in Abadi et al. 2003; Brook et al. 2004, 2005). Overall, our results require that some disk heating occurs at intermediate ages (to puff up the AGB component) but that events at earlier times (interactions or mergers) created a majority of the RGB stars over a short timescale.

Finally, we present tenuous evidence for an extended old component seen only at disk heights $\gtrsim 2$–3 kpc. At large scale heights we see marginal overdensities of stars in the RGB profiles of Figure 7. There also seems to be a reduction in the metallicity of RGB stars at this height (Fig. 12). In one of our galaxies, Tikhonov et al. (2005) find strong evidence for a very extended component of RGB stars, extending from $\sim 2$ to 7 kpc. While this component appears to have an exponential distribution, its $z_p$-value of $\sim 2$ kpc (compared to a radial scale length of $\sim 1$ kpc) strongly suggests it is not a disk. These extended components are detected at about the height at which the halo becomes prominent in the stacked Sloan images of Zibetti et al. (2004). However, based on our observations, we are unable to assess the properties or frequency of these components.

The present-day structure of galaxy disks results from a complex mixing of effects, and a full explanation requires detailed knowledge of the SFH, merging events, and disk heating. Studies such as the one presented here help to disentangle these effects and determine their relative importance as functions of galaxy type and mass. This study also shows the promise that HST observations of resolved stars have for enabling the detailed analysis of low surface brightness stellar components in galaxies outside the Local Group. A comparison of our data with N-body simulations of low-mass disk galaxies would assist in constraining disk heating and merging scenarios. Unfortunately, current simulations of disk galaxy formation have focused on massive galaxies like the Milky Way (Abadi et al. 2003; Brook et al. 2004, 2005). Also, deeper observations that fully resolve the red and blue horizontal branches would greatly improve constraints on the SFHs of these galaxies and improve our understanding of their structure.

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