RED THICK DISKS OF NEARBY GALAXIES

JEREMY MOULD
National Optical Astronomy Observatory, P.O. Box 26732, Tucson, AZ 85726-6732, jrm@noao.edu
Received 2004 August 18; accepted 2004 November 5

ABSTRACT

Edge-on systems reveal the properties of disk galaxies as a function of height, z, above the plane. Four local edge-on galaxies that are close enough to have been resolved into stars by the Hubble Space Telescope show thick disks composed of a red stellar population that is old and relatively metal rich. Color gradients, \( \Delta(V - I)/\Delta z \), are zero or slightly positive. Favored models may have an explicit thick disk formation phase.

Key words: galaxies: formation — galaxies: stellar content

1. INTRODUCTION

Thick disks were discovered twenty five years ago (Gilmore & Reid 1983, Burstein 1979), but only the most basic constraints have subsequently been set on their origin in the structural formation of galaxies. An understanding of thick disks lies at the heart of the set of physical questions about the origin and evolution of disks in galaxies. The shredding of satellite galaxies, the triggering of star formation in disk gas by mergers, and the early evolution of disks in protogalaxies while they are still out of dynamical equilibrium, are three key processes that must contribute to the thick disk fossil record. Observations and simulations provide significant opportunities to diagnose the relative importance of these three processes and to discover other processes.

Recent developments in theory and observation include the work of Abadi et al. (2003), who point to a primary role for residual stars from merged dwarfs, and Dalcantone et al. (2004), who find a critical mass (or rotation velocity) below which star formation efficiency may be markedly lower. Other, only slightly less recent work that bears directly on these disk formation and evolution processes is by Domínguez-Tenreiro et al. (1998) and Johnston et al. (2001). Most recently, Brook et al. (2004) have explored early results from chemo-dynamical cosmological simulations and identify thick disk formation with a \( z > 2 \) epoch of chaotic merging of multiple peer disks of mixed gas and stars.

New insight into the disk component of galaxies finds that thick disks are prevalent, old, and red. Dalcanton & Bernstein (2002) find these properties in surface photometry of an edge-on sample and argue that they are the markers of an early epoch of merging experienced by all disk galaxies. If this is the case, the resolved stellar population of an edge-on nearby sample of disk galaxies should show both the characteristic age and metallicity profile of a posthalo epoch of star formation 6–12 Gyr ago.

A suitable sample for study of \( (I, V - I) \) color-magnitude diagrams (CMDs) consists of the closest galaxies with axial ratios less than 0.25. Galaxies in the NASA/IPAC Extragalactic Database (NED) whose redshifts imply a distance less than 25% that of the Virgo Cluster according to Mould et al. (2000) and with \( A_H < 1 \) are ESO 318-G3, ESO 383-G91, NGC 784, 1560, 4144, 4244, IC 3308, UGC 1281, 7321, 11583, and UGCA 442. Those with available Wide Field Planetary Camera 2 (WFPC2) data are NGC 784, NGC 1560, UGC 1281, UGC 7321, UGCA 442, and IC 3308. UGC 1281 (Matthews et al. 1999) and IC 3308 are not well resolved by WFPC2. In the present paper we analyze NGC 784, NGC 1560, UGC 1281, and UGCA 442. They span a range of rotation velocities from 95 to 150 km s\(^{-1}\) (21 cm line full width at 20% peak).

WFPC2 on the Hubble Space Telescope (HST) reaches below the tip of the red giant branch (TRGB) in these galaxies, allowing us to diagnose the star formation history of their thick disk stellar populations. The color of the RGB in the magnitude fainter than the tip tells us the metallicity of the population (Da Costa & Armandroff 1990). Another diagnostic tool is the extended giant branches of Magellanic Cloud star clusters in this age range, in which the luminosity difference between the asymptotic giant branch (AGB) tip \( (M_{bol,\,TRGB}) \) and the TRGB \( (M_{bol,\,TRGB}) \) is a measure of age (Mould & Aaronson 1982; Frogel et al. 1990) and the fuel-burning theorem (Renzini & Buzzoni 1986) tells us the star formation history of the region.

This project is intended to lay foundations for a larger study of the formation epoch of local galaxies that will complement the analysis of that epoch obtained by “looking back” at very distant galaxies. Freeman & Bland-Hawthorn (2002) offer the prospect that the chemical and kinematic evolution of the early history of disks may be deterministically unraveled in detailed spectroscopic studies with large telescopes. The present study is a start on the reconnaissance of the region from 0 to 5 Mpc to be explored in this way, using simple photometry of resolved stars.

2. COLOR-MAGNITUDE DIAGRAMS OF FOUR EDGE-ON DISK GALAXIES

The HST archive contains WFPC2 images of four of the sample galaxies listed in Table 1. The relevant observational parameters are noted in columns (3) and (4). Column (5) of Table 1 is the Galactic extinction in \( I \) magnitudes drawn from NED. This database is also the source of the axial ratios (col. [2]), which quantify the edge-on morphology of the galaxies. Images of the galaxies made with standard STSDAS-IRAF cosmic-ray rejection are reproduced in Figure 1.

Photometry of all four chips in both filters in all four galaxies was carried out using DAOPHOT (Stetson 1987) and ALLSTAR (Stetson 1994). Stars were detected at the 2 \( \sigma \) level on the images, and WFPC2 point-spread functions were taken from Stetson et al. (1998), following the practice of the Hubble Constant Key Project (Kennicutt et al. 1995). Linking the frames was achieved trivially with DAOMASTER, since all images were undithered and single epoch. The calibration and charge transfer efficiency corrections of Dolphin (2002) were adopted.\(^1\) Aperture corrections were measured using bright stars cleaned with SUBSTAR. The four CMDs are shown in Figures 2–5.

\(^1\) Available at http://purcell.as.arizona.edu/~andy/wfpc2_cali.
| Galaxy      | Axial Ratio | Filters        | Exposure Time | $A_I$  | $(m-M)_V$ |
|------------|-------------|----------------|---------------|--------|-----------|
| NGC 1560   | 0.16        | F606W, F814W   | 600           | 0.365  | 27.6 ± 0.15 |
| UGC 1281   | 0.11        | F606W, F814W   | 2 × 300       | 0.09   | 28.1 ± 0.15 |
| NGC 784    | 0.23        | F606W, F814W   | 2 × 300       | 0.115  | 27.4 ± 0.15 |
| UGCA 442   | 0.14        | F606W, F814W   | 600           | 0.032  | 27.9 ± 0.15 |

Notes.—Cols. (2) and (5): Source: NED. Cols. (5) and (6): Magnitudes. Col. (6): Apparent distance moduli derived in § 2.

Fig. 1a

Fig. 1.—(a) NGC 784 imaged by WFPC2. (b) NGC 1560. (c) UGC 1281. (d) UGCA 442 = ESO 471-G6.
Fig. 2.—(a) CMD for NGC 784. Bottom: Stars within 200 pixels of the midplane of the galaxy. Top: Stars more than 500 pixels from the midplane of the galaxy. Middle: Those in between. (b) CMD for NGC 784. Top left: All stars. Top right: The $I$-band giant branch luminosity function for $1 < V - I < 2$; the thick histogram refers to those stars more than 200 pixels from the midplane of the galaxy. Bottom left: Sakai et al. (1996) edge detector for the TRGB. Bottom right: Stars more than 200 pixels from the midplane of the galaxy.
Fig. 3.—Same as Fig. 2, but for NGC 1560.

Fig. 3a

Fig. 3b
Fig. 4.—Same as Fig. 2, but for UGC 1281.
Fig. 5a

Fig. 5b

Fig. 5.—Same as Fig. 2, but for UGCA 442.
In all four CMDs the upper AGB is prominent but confined to the plane of the galaxy. In the giant branch luminosity function, a rapid rise at \( I \) magnitudes between 23 and 24 corresponds to the tip of the RGB. The "edge detector" of Sakai et al. (1996) is then used to effectively differentiate the luminosity function. The tip of the RGB is thereby detected as a peak (Figs. 2b–5b, bottom left), allowing the distance of each galaxy to be measured (Madore & Freedman 1998 and references therein). Bellazzini et al. (2001) find:

\[
M_{\text{TRGB}} = -0.14 \left[ \frac{\text{Fe}}{\text{H}} \right]^2 + 0.48 \left[ \frac{\text{Fe}}{\text{H}} \right] - 3.66.
\]

Adopting \(-1 < \left[ \frac{\text{Fe}}{\text{H}} \right] < -0.3\), we calculate a calibration uncertainty \( \Delta M_{\text{TRGB}} = \pm 0.10 \) mag. Observational uncertainty is explored in the Appendix by means of artificial star experiments. Apparent distance moduli are reported in column (6) of Table 1. The quoted uncertainty reflects chemical, calibration, and observational uncertainties in \( M_{\text{bol}, \text{TRGB}} \).

The question arises whether the RGB tip distance may be affected by internal reddening in the plane of each galaxy. Comparing the bottom two panels in Figure 3b, we see no difference in the RGB tip on and off the plane of NGC 1560 and 0.2 mag difference in UGCA 442 and UGC 1281. The luminosity function statistics of NGC 784 makes such a comparison noisy and difficult, but an upper limit of 0.6 mag can be set. For galaxies of this morphological type (\( T \geq 6 \)), Han (1992) finds \( \Delta I = 0.33 \pm 0.14 \) to \( 0.49 \pm 0.22 \) mag for galaxies with this range of axial ratios. These values are probably an upper limit on the extinction of the old red giants and only relevant to the plane of the galaxies. As a possible systematic error, the on- and off-the-plane difference in \( M_{\text{TRGB}} \) is added directly to the distance error estimate in Table 1, rather than in quadrature, as would be appropriate for random errors.

Other measurements of the distances of these galaxies are sparse. NGC 1560 is a member of the Maffei group of galaxies according to Kraan-Korteweg (1985, hereafter KK85), who places NGC 1560 at 0.20 times the distance of the Virgo Cluster. That yields 3.0 Mpc from the Virgo distance of Mould et al. (2000), which can be compared with 3.3 \( \pm 0.2 \) Mpc for our distance for NGC 1560. KK85 has UGCA 442 as a member of the Sculptor group, 3.4 \( \pm 0.3 \) Mpc away according to Aaronson & Mould (1983). Our UGCA 442 distance is 3.8 \( \pm 0.8 \) Mpc. The other galaxies are field galaxies. UGC 1281 is approximately 0.3 times the distance of Virgo according to KK85, or 4.5 Mpc, compared to our measured 4.2 \( \pm 0.9 \) Mpc. For NGC 784 the comparison is 5.4 (from KK85), cf. 3.0 \( \pm 1.2 \) Mpc. With the exception of the last, the agreement is satisfactory for present purposes, but, as a caveat, we note that our distances are uncorrected for internal extinction and that alternative distances from Virgocentric flow models are subject to random velocities.
that are a significant fraction of the recession velocity. Other TRGB distances are given by Karachentsev et al. (2003a, 2003b).

3. VERTICAL COLOR GRADIENTS

As a measure of a mean color for the giant branch in these CMDs, it is straightforward to define an error-weighted average of the \( V - I \) colors of stars within a broad color window of the RGB/AGB. The window was defined by \( 0.80 < V - I < 2.34 \) and \( 19 \text{ mag} < I < 26 \text{ mag} \). The lower limit on color excludes main-sequence stars and blue supergiants. The upper limit on magnitude excludes red horizontal-branch stars but includes red supergiants. This window is consistent for all four galaxies and for the models described in § 4. Figure 6 shows the color gradient in this \( \langle V - I \rangle \) normal to the projected plane of the disk. Since reddening might affect the colors in the thin disk within a few hundred parsecs of the midplane, colors are not plotted close to the plane. No correction has been made for interstellar reddening in Figure 6. No correction is required for foreground stars, which are few in number. For example, for NGC 1560, the lowest latitude member of the sample, the Bahcall & Soneira (1986) model of the galaxy predicts seven foreground stars in the color window defined above with \( 19 < V < 27 \). The mean color is \( V - I = 1.6 \), based on a standard \( (B - V, V - I) \) diagram, very similar to the color of the giant branch stars themselves.

The noteworthy feature of Figure 6 is the weakness of the color gradient in the disks of these galaxies out to 2 kpc from the plane. The average over the four galaxies is \( 0.06 \pm 0.02 \text{ mag kpc}^{-1} \) in the sense that the thick disk is redder farther from the thin disk at the 3 \( \sigma \) level. Column (2) of Table 2 records the weighted average \( V - I \) for the region of the disk beyond 900 pc, and column (3) gives the reddening in the Milky Way according to NED and Schlegel et al. (1998). The giant branches of the thick disk regions of these galaxies are consistently red, with \( V - I \) colors ranging from 1.39 to 1.56 (col. [4]). The bluest color is that of the least luminous and least massive galaxy, UGCA 442, judging by the luminosities and 21 cm line widths in columns (5) and (6).

In conclusion, there is a general tendency for the giant branch of the stellar population in the thick disks of these galaxies to show color gradients, \( \Delta(V - I)/\Delta z \), that are zero or slightly positive. This puts significant constraints on their star formation and chemical enrichment history.

4. STAR FORMATION AND CHEMICAL ENRICHMENT HISTORY

Measurement of metallicity from \( (V, I) \) CMDs in stellar populations of the age of globular clusters is well understood (Da Costa & Armandroff 1990; Harris & Harris 2002 and references therein). For younger ages, the location of the RGB depends on both age and metallicity, and it is necessary to refer directly to the predictions of stellar evolutionary models and synthesize the observable quantities from them. To match the observations, a weighted average \( V - I \) color of RGB/AGB stars brighter than \( M_I = -3 \) can be computed from the Padua isochrones (Girardi et al. 2000) for selected values of the age, \( t \), and metallicity, \( Z \), of stellar populations. If we assume that the disk formed stars over an astration time (i.e., time to make stars), which may be short or long compared with the overall history of the disk, we have the models depicted in Figure 7. Colors were computed as a sum over four values of \( Z = (0.0004, 0.001, 0.004, 0.008) \) with a starting age of 12.6 Gyr and with convective overshooting assumed. These models show a weak dependence of color on timescale and a much stronger dependence on the final metallicity that the disk attains.

The colors of these models match the colors we observe for the giant branches of the thick disks in the four galaxies of the sample: they bound the range of colors. We conclude that in the present sample (average luminosity \( \sim 10^8 L_\odot \)), thick disks reached \( Z = 0.004 - 0.008 \), i.e., one sixth to one third solar abundance, in an astration time that is unconstrained by the present data. The mean heavy-element abundances of the stellar populations in these models are \( Z = 0.0018 \) and 0.0034, i.e., [Fe/H] = −1.0 and −0.78, respectively. The very slight color gradient in the thick disk (0.06 ± 0.02 mag kpc\(^{-1}\)) corresponds to a deficit in heavy elements of approximately 30% at \( z = 1 \text{ kpc} \) relative to \( z = 2 \text{ kpc} \) from the midplane of the disk or a stellar population

![Fig. 7.—Mean \( V - I \) color of the mean giant branch with \( M_I < -3 \text{ mag} \) in the Padua isochrones as a function of the time to enrich the stellar population from \( Z = 0.0004 \) to 0.008 (filled symbols) or to \( Z = 0.004 \) (open symbols).](image-url)
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This technique to a height of 1 kpc from the plane.

Sampling statistics illustrated in Figure 9 limit the sensitivity of

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stars of age 2

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0.004, 0.001, 0.004, and 0.008.

where the partial derivatives are approximately 0.55 and 0.2,

respectively, according to the models.

The models can also be used to diagnose the age of the stellar

population from the CMDs. The behavior of an AGB/RGB ratio

formed from the ratio within the giant branch color window of

stars in the interval (21, 23) to stars in the interval (24, 25) in I

magnitude is shown in Figure 8 as a function of age for distances

of 3–5 Mpc. The ratio is an effective tracer of stellar populations

between 2 × 10⁸ and 2 × 10⁹ yr in age, as demonstrated in Mag-

gellanic Cloud star clusters by Frogel et al. (1990). Column (7) in

Table 2 records this AGB/RGB ratio within 100 pixels (<200 pc)

of the plane of each galaxy. As shown in Figure 9, NGC 784 and

1560 have substantial intermediate-age populations confined to

a thin disk. These are the only sites in the disks we have sam-

pled where there are intermediate-age populations of significance.

Sampling statistics illustrated in Figure 9 limit the sensitivity of

this technique to a height of 1 kpc from the plane.

5. DISCUSSION

In a recent review Wyse (2005) considers five possible

models for the origin of thick disks.

1. The flattened stellar halo. According to Gilmore & Wyse

(1985), the Milky Way’s thick disk has a distinct chemistry from

its halo, but further work, involving fields ~10⁷ from the galaxy,

would be required to test the equivalent hypothesis for the pres-

ent sample.

2. The heated thin disk. The classical source of heating is
density inhomogeneities (Wielen & Fuchs 1985). Two alternate

sources of heating are star formation and mergers. However,

stars of age 2 × 10⁸–2 × 10⁹ yr are confined to the thin disk in the

present sample. This model is not supported by the data, al-

though interactions with galaxies more than 3 Gyr ago can cer-

tainly not be ruled out as heating sources.

3. Dissipative disk formation. Disk settling on timescales

longer than the enrichment timescale gives rise to metallicity

gradients (Burkert et al. 1992) of order a factor of 2 kpc⁻¹ from

z = 0.5 to 1.5 kpc and steeper elsewhere. This model is not

supported by the data, which show reverse color gradients close
to zero. It is contrived to suppose that reverse color gradients
could arise from increasing dustiness further from the plane,

although a better test of that hypothesis than stellar photometry

might be deep surface photometry, which would be able to detect

individual dust clouds. The models of § 4 imply that age gra-
dients are unable to null out metallicity gradients as steep as

the dissipative models predict.

4. Accretion from shredded satellites. This model predicts

metal-poor thick disks, characteristic of their dwarf components.

For example, adding a 10⁷ L⊙ thick disk ([Fe/H] ≈ −1.9) to a

10⁸ L⊙ galaxy ([Fe/H] ≈ −1.4) would yield a color difference

corresponding to a factor of approximately 3 in Z, according to

current evidence on the mass-metallicity relation for galaxies,

e.g., Tamura et al. (2001). This model in its simplest form is not

supported by the data, which show reverse color gradients close
to zero.

5. The primordial thick disk. In this model the thick disk is

simply the oldest component of a total galaxy disk that formed

over billions of years. According to Brook et al. (2004), the

formation of the early thick disk may have involved a chaotic

period of accretion at high redshift. Accretion from shredded

satellites is involved in this process, but if the accreted satellites

have high gas fractions, astration during and after the merger and

the consequent enrichment can eliminate (fully or partly) the

difference between the metallicities of the newly arrived and the

original material. Models of this nature should be explored as

likely fits to data of the present kind.

6. CONCLUSIONS

The thick disk stellar populations of a sample of resolved,

edge-on, dwarf galaxies are old and relatively metal rich (one-
sixth to one-tenth solar abundance in mean metallicity). The

intermediate-age population is confined to the thin disk. Color

gradients are very slight and, in fact, barely detected. Models

involving disk heating or halo flattening are not natural fits to

the data because they differ in enrichment and age from the ob-

served stellar population. Models involving dissipative col-

lapse tend to predict an unobserved chemical gradient. Dwarf

merger models are problematic if complete astration occurs

before accretion.
Instead, with the caveat that the present sample is confined to a low-mass subset, the present data seem to favor a high-redshift or primordial origin to the thick disk, possibly in a chaotic gas-rich merger environment. The observations are consistent with the ideas of Dalcanton & Bernstein (2002), who infer from surface photometry of a large sample that thick disks are a standard phase in the early formation of disk galaxies. Resolution into giant branch CMDs helps separate age and metallicity effects in analyzing stellar populations. It is therefore desirable to extend the present study to a larger sample of less dwarfish galaxies using the Advanced Camera for Surveys on HST.

I would like to thank the School of Physics of the University of Melbourne for their hospitality while the first draft was being written. I also acknowledge the help of an anonymous referee whose comments improved the paper materially. This research has made use of NED, which is operated by the Jet Propulsion Laboratory for NASA, and the HST archive, which is operated by the Space Telescope Science Institute (STScI) for NASA. Images were processed with IRAF, which is maintained by the National Optical Astronomical Observatory (NOAO). NOAO and STScI are managed by the Association of Universities for Research in Astronomy, Inc., for the agencies.

APPENDIX

Although accurate distances are not essential to this investigation, it is of interest to examine the effects of incompleteness on the TRGB distances reported in Table 1. For this purpose in both filters, we added 200 stars per chip to each of the four galaxies for which CMDs have been obtained, employing a uniform spatial and magnitude distribution in the range 22.8 mag < I < 25.8 mag (0.75 mag fainter in NGC 1560 and UGCA 442). The measured incompleteness is displayed in Figure 10.

Because the RGB tip lies in a region where completeness declines slowly and linearly with increasing magnitude, completeness corrections are negligible relative to the uncertainties arising from limited knowledge of reddening and metallicity. The color gradients measured in §3 were also found to be robust against incompleteness.

Fig. 10.—Completeness-corrected edge detector for the TRGB (bottom). Fake star experiments allow the completeness to be estimated, and this is shown chip by chip in the top panels. The left-hand panels are NGC 784 (solid lines) and UGC 1281 (dashed lines). The right-hand panels are NGC 1560 (solid lines) and UGCA 442 (dashed lines). The completeness-corrected TRGB edge detector is displayed with the same galaxy key.
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