THE STELLAR POPULATIONS OF M 33’S OUTER REGIONS II: DEEP ACS IMAGING

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ABSTRACT

Studying the stellar populations in the outskirts of spiral galaxies can provide important constraints on their structure, formation, and evolution. To that end, we present V I photometry obtained with the Advanced Camera for Surveys for three fields located 20°-30° in projected distance southeast of M 33’s nucleus (corresponding to 4-6 visual scale lengths or 9-13 kpc in deprojected radius). The color-magnitude diagram reveals a mixed stellar population whose youngest constituents have ages no greater than 100 Myr and whose oldest members have ages of at least several Gyr. The presence of stars as massive as 3 M⊙ is consistent with global star formation thresholds in disk galaxies but could argue for a threshold in M 33 that is on the low end of observational and theoretical expectations. The metallicity gradient as inferred by comparing the observed red giant branch (RGB) to the Galactic globular clusters is consistent with M 33’s inner disk gradient traced by several other studies. The surface density of RGB stars drops exponentially with a radial scale length of 470±50 kpc. The scale length increases with age in a manner similar to the vertical scale height of several nearby late-type spirals. Based on the metallicity gradient, density gradient, and mixed nature of the stellar populations, we conclude these RGB stars are not dominated by a disk population although we cannot rule out the presence of a small halo component.

Subject headings: Local Group (galaxies: individual M 33) (galaxies: stellar content) (galaxies: evolution) (galaxies: structure) (galaxies: abundances)

1. INTRODUCTION

Stars are the most visible building blocks of galaxies. Hence, knowledge of the ages and chemical compositions of a galaxy’s stellar populations can yield insights into its formation and evolution and the astrophysical processes involved. Studies seeking to understand disk galaxy evolution typically use integrated colors of large samples of galaxies at various redshifts to infer mean ages and metallicities. However, integrating the light from all the stars in an entire galaxy or any portion of a galaxy can reduce information while increasing uncertainties.

That is why it is important to more fully understand nearby systems whose stellar contents we can directly resolve. Such systems provide benchmarks for their more distant, unresolved counterparts. An example of such a system is M 33, the third most massive spiral galaxy in the Local Group. In addition to being one of the most massive on types of spirals in the Universe (de Vaucouleurs 1963), it is also the only other known spiral in the Local Group besides the Galaxy and M 31. Therefore, understanding M 33’s evolution is an important step toward understanding the evolution of spiral galaxies in general.

Unlike its larger, more massive spiral counterparts in the Local Group, M 33 has a late-type morphology (Sb type of Scd). Like any late-type spirals, it has a relatively low dark halo virialized mass of 10^{11} M⊙ (Corsini 2003) and high total gas mass fraction of 0.02-0.04 (Garnett 2002; Corbelli 2003). Some empirical and theoretical studies predict such galaxies to have evolutionary histories different from those of earlier/morphological types (e.g., Scannapieco & Tessera 2003; Garnett 2002; Ferreras et al. 2004; Dalcanton et al. 2004; Haines et al. 2004). Hence, M 33 potentially provides a contrasting view of galaxy evolution that is provided by the Galaxy and M 31.

The outer disks of spiral galaxies are unique environments for several reasons. They are often characterized by warps, arms, and other effects of gas inflow or gravitational interactions with nearby galaxies. The disk gravitational potential is relatively shallow and the spiral features weak compared to the inner disk. Moreover, H I has a low column density but dominates the total baryonic mass.
What processes affect the star formation rates in such environments? Some possibilities include galactic winds, in which gas is lost from the disk, interactions with dense waves, rotational shear, and viscous radial gas flows. Ferguson et al. (1998) discovered H II regions organized in spiral arms out to 2 optical radii in three late-type disk galaxies. The recent discovery of extended UV disks in several galaxies further raises the importance of spiral structure in driving star formation in the outer regions of these galaxies (GildePaz et al. 2005). In addition, the UV and x-ray backgrounds as well as feedback from massive stars could be more important regulators of star formation in the tenuous gas of outer disks than in inner disks where dense molecular cores are readily shielded from dissociation and ionization.

The stellar populations in the outskirts of disk galaxies can contain important clues to the interplay between these processes. Furthermore, they tell us about the galactic collapse history, conditions in the early halo, and the progression of subsequent star formation (Freeman & Bland-Hawthorne 2002). For example, the disk truncation seen in optical surface photometry of many galaxies could be associated with a critical gas density for star formation (e.g., Naab & Ostriker 2006) or the maximum specific angular momentum of the baryons before the protogalactic cloud collapsed (e.g., van der Kuit 1987; Pohlen et al. 2000; de Grijs et al. 2001).

In Tiede et al. (2004; Paper I) we used ground-based photometry reaching the horizontal branch to study the metallicity and spatial distribution of stars in M 33's outskirts. The primary conclusion was that the metallicity gradient was consistent with that of M 33's inner disk implying that the disk extends out to a deprojected radius of at least $R_{dp}$ 10 kpc. The present paper is a natural follow-up to Paper I because we use deeper photometry obtained with the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope (HST) that enables a more comprehensive examination of stellar ages, metallicities, and spatial distribution in M 33's outer regions. In a companion paper (Barker et al. 2006; Paper III) we present a complementary yet distinct analysis of the detailed star formation history of this region based on the ACS data.

This paper is organized as follows. In Section 2 we describe the observations and photometric reduction procedure, we present and discuss the resulting color-magnitude diagrams in Section 3. In Section 4 we investigate the stellar surface density. Then in Section 5 and 6 we derive the metallicity distribution functions and compare them to measurements reported in the literature in the context of M 33's metallicity gradient. Finally, in Section 7 and 8 we discuss the implications and summarize the results.

In this paper, age means lookback time (i.e., time from the present) and the global metallicity is $Z/M$. $\log[Z/Z_{\odot}]$ where $Z = 0.019$. For M 33's distance, inclination, and position angle we assume, respectively, 867 and 28 kpc (Paper I; Gallart et al. 2004), 56 , and 23 (Cioni et al. 1997; Regan & Vogel 1994).

2. OBSERVATIONS AND PHOTOMETRY

2.1. ACS

We make use of observations obtained with ACS during Cycle 11 program GO-9479. Three fields were observed at projected radii of approximately $20^0$ and $30^0$ southeast of M 33's nucleus or $R_{dp}$ 9–13 kpc. The locations of the fields are shown in Figure 1. Each field was observed for a total of 760 s and 1400 s in the F606W and F814W filters, respectively. The observations for each field were divided into two CR-SPLIT exposures to allow identification and masking of cosmic rays. No dithering was carried out. Hence, we will refer to the ACS fields as A1, A2, and A3 in order of increasing galactocentric distance. The observations are summarized in Table 1.

The data were retrieved from the Space Telescope Science Institute (STScI) after going through the standard CALACS pipeline and "on-the-fly" processing. This processing generated FITL images which were bias and dark subtracted and at- ekaied. Because ACS at- ekaied images are designed to at- ekaied a source with uniform surface brightness rather than preserve total integrated counts, it was necessary to multiply the FITL images by the pixel area maps provided on the STScI website.

Since these at- ekaied images are sparse, there were not enough bright stars to produce a point-spread function (PSF) with a sufficient signal-to-noise ratio. So an aperture high signal-to-noise ratio PSF was constructed...
For each M 33 field we first used Source Extractor (Bertin & Arnouts 1996) to identify sources, DAO PHOT to measure aperture magnitudes, and ALLSTAR to measure PSF magnitudes. This process was repeated on the resulting subtracted image to catch any stars that were missed. Then we input the star lists into DAO MASTER to derive precise spatial coordinate transformations between the frames in each field. This allowed us to coadd all the frames to produce one single image in each field. This image in age was then run through two iterations of Source Extractor, DAO PHOT, and ALLSTAR as before. The resulting list of objects and individual CR-SPLIT exposures were input into ALLFRAME to obtain the final PSF magnitudes (Stetson 1987; Stetson & Harris 1988; Stetson 1993; Stetson 1994).

We derived mean aperture corrections from 50 to 100 bright, isolated stars in A1. The standard deviations of the aperture corrections ranged from 0.02 to 0.03 mag while the standard error of the mean was always < 0.01 mag. There were not enough bright stars to derive reliable aperture corrections in A2 and A3. Since the ACS grids overlapped, we identified 200 stars in common on between A1 and A2 and 40 between A2 and A3. From these stars we calculated a mean of 20 sets to bring the PSF magnitudes of A2 and A3 onto the same scale as A1. The standard deviation of each group of 20 sets was 0.05 mag while the standard error of the mean was < 0.01 mag. We applied the appropriate CTE corrections following the prescription in Riess & Mack (2004). These corrections were usually < 0.005 mag.

To convert the aperture magnitudes to the standard UBVRI system, we used the theoretical transformation of Sirianni et al. (2005). These authors quote an uncertainty of 0.05 mag for this transformation which we adopt as the uncertainty in the photometric zero-point in the present study.

To reduce spurious detections (e.g. incompletely masked cosmic rays, background galaxies, noise, etc.) we made cuts on the final catalog according to the following criteria. An object was kept if it was detected on all CR-SPLIT exposures, if < 3 of the median at its magnitude, sharp < 3 of the median sharp at its magnitude, jsharp < 0.5, and error < 2 times the median error at its magnitude. The parameter m measures the quality of the PSF t and sharp m measures the sharpness or spatial extent of the object. There were 22415, 7666, and 3337 stars in the final catalogs for A1, A2, and A3, respectively.

We ran a series of extensive artificial star tests to accurately estimate the photometric errors and completeness rates. For each field we generated two catalogs of artificial stars with known magnitude. The magnitude in the first catalog were chosen in m in the observed distribution of stars in the CMD. Regions with no observed stars were assigned a magnitude number of artificial stars to fully cover the CMD. The second catalog was compiled from the unscattered magnitudes of the observed stars by filling the synthetic CMDs described in Paper III. This ensured a more complete sampling of the error and completeness functions because it focused on regions where the true stellar colors and magnitudes are expected to lie. In total, 10^6 artificial stars were generated for each field.

The artificial stars were inserted into the original frames using the same PSFs that we used to photometer the original frames. We placed the stars on a regular grid such that the spacing between them was 2.1 PSF seeing radii (42 pixels). This distance was chosen as a compromise between the requirement that the artificial stars not change the crowding conditions and the need for high computing efficiency. To fully sample the PSFs, we randomly varied the starting position of the grid and allowed for sub-pixel positions. The images were then photometered in exactly the same manner as before us-
ing exactly the same detection requirements.

In Figure 2 we show the difference between input and output magnitude as a function of input magnitude for all recovered stars in eld A1. The gray points are the individual artificial stars while the black squares and error bars represent the median and standard deviation in bins 0.4 mag wide. This gure shows how a star is likely to get redistributed in the CMD if you know where it originates before the measurement process. For most of the magnitude range covered in each band, there is no signicant difference between the input and output magnitudes. However, stars with input magnitudes $V_{in} < 27.5$ or $I_{in} < 27.0$ tend to be recovered brighter than their true magnitudes because measuring errors or random uncertainties in the unresolved background light may scatter faint stars below the detection limit (Stetson & Harris 1988; Gallart et al. 1995; Bellazzini et al. 2002b).

In Figure 3 we show the variation of the completeness rate with input magnitude and color for A1. The solid, dotted, and dashed lines correspond to the color ranges $0.5 < (V - I) < 0.5$, $0.5 < (V - I) < 1.5$, and $1.5 < (V - I) < 2.5$, respectively. The completeness rises rapidly from the faint end and, due to our detection requirements and the presence of cosmic rays and bad pixels, levels off at 90% at $V_{in} = 26.0$ and $I_{in} = 25.0$. The completeness rate reaches 50% at $V_{in} = 27.4$, $28.2$, and $I_{in} = 26.2$, $27.0$ depending on the color. The errors and completeness rates for A2 and A3 are similar to within 3% over most of the magnitude range (i.e., crowding is not a strong limiting factor).

22. W FPC2

Parallel observations were also taken with the Wide Field and Planetary Camera 2 (W FPC2). The exposure times were 280 s in F605W and 1000 s in F814W divided into two CR-SPPLIT exposures per filter. Figure 4 shows the locations of the elds which will be referred to as W 1, W 2, and W 3 in order of increasing galactocentric distance. Table 1 contains the exposure information.

We elected to use HST phot (Dolphin 2000) rather than DAO PHOT to obtain PSF photometry. Our experience has been that the former is superior in computational efciency but the latter is superior in photometric depth. Since the W FPC2 exposure times are relatively short the extra photometric depth gained by using DAO PHOT was not worth the extra computational time.

Photometry was obtained following the cookbook procedure in the HST phot manual. In sum, mosaic bad pixels, cosmic rays, and hot pixels were masked and the two images in each filter were coadded. Then HST phot was run with individual filter and total detection thresholds of 1 and 2, respectively. We enabled the options to re.sky and perform a weighted PSF that gives the central PSF pixels more weight during the tting. To reduce spurious detections in the nal catalogs we required $I < 26$, $S=N > 5$, and $jsharp < 0.5$. Even after these cuts we had to remove 72, 154, and 30 stars from the catalogs which were artifacts from the diraction spikes of bright foreground stars. The nal catalogs then contained 648, 429, and 433 stars.

3. COLOR-MAGNITUDE DIAGRAMS

The CMDs for A1 and A3 are presented in Figures 4 and 6. Qualitatively, they bear some resemblance to the CMDs of M 33’s inner disk which were obtained with W FPC2 and presented in Sarajedini et al. (2000). The most prominent features in all three CMDs are the red clump (RC) at $I = 24.4$ and red giant branch (RGB) whose brightest stars reach a color of $(V - I) = 0$ and a red supergiant (RSG) sequence (sometimes referred to as the ‘vertical clump’ extending from the top of the RC and adjacent to the RGB.

The CMD for eld A1 is reproduced in Figure 7 with isochrones from Girardi et al. (2002) overplotted assuming a foreground reddening of $E(V - I) = 0.06$ $0.02$ (Meu.ca & Kristian 1986; Sarajedini et al. 2000) and extinction $A_V = 1.31 E(V - I)$ (von Hippel & Sarajedini...
Fig. 4. | CMD of field A1. The main features are the RC at I = 24.4, the RGB extending from the RC to brighter magnitudes, and the blue plume of younger MS stars at $(V - I) = 0$.

Fig. 5. | Same as Fig. 4 but for field A2.

Fig. 6. | Same as Fig. 4 but for field A3.

Fig. 7. | CMD of A1 with isochrones from Girardi et al. (2002) overplotted. The isochrones have a metallicity of $[M/H] = 0.7$ and ages of 100 Myr, 398 Myr, and 1.0, 2.0, 5.0, and 7.9 Gyr from top to bottom, respectively. The three horizontal lines mark the 100 Myr MS locations of 5, 4, and 3 M$\odot$ from top to bottom, respectively.

1998). The pair of isochrones overlapping the MS have a global metallicity $[M/H] = 0.7$ and ages of 100 and 398 Myr. The three horizontal lines mark the MS positions at 5, 4, and 3 M$\odot$ from top to bottom, respectively, for the 100 Myr isochrone. In A1, the brightest MS stars have masses close to 5 M$\odot$. In A2 and A3 there are only a handful of possible MS stars with masses above 4 M$\odot$ and 1-2 dozen with masses in the range 3-4 M$\odot$. The termination of the MS in A1 provides an upper limit of 100 Myr to the ages of the youngest stars.

The mean color error at $I = 24$ is only 0.05 mag while the width of the MS at this magnitude is 0.2 mag. This indicates an intrinsic color spread to the MS which could be due to a spread in metallicity, age, reddening or some combination thereof. A metallic spread alone would have to be several tenths of a dex because the MS for $[M/H] = 0.2$ is only 0.06 mag redder at $I = 24.0$ than that for $[M/H] = 0.7$. There is evidence for an age spread in the MS because a single age cannot simultaneously account for the bright MS turn-off and the presence of the RSG sequence extending from the top-left of the RC. The isochrones indicate the RSG sequence is probably a few hundred Myr older than the youngest MS stars. Sarajedini et al. (2006) estimated a typical disk reddening off $(V - I) = 0.3$ based on M 33 RR Lyraes located at $R_d = 13.5$. Reddening values that large in field A1 would be surprising given that it is located almost 3 times farther out. However, little is known about the distribution of dust in M 33 so we cannot rule out some contribution to the MS width due to dust.

The 2-8 Gyr isochrones in Fig. 7 indicate an age
spread of several Gyr could account for much of the RGB width. However, metallicity has a larger effect on the color of the RGB than age. Because of the well-known age-metallicity degeneracy, multiple combinations of age and metallicity are consistent with the position of the RGB. To get a rough idea of which ages and metallicities, we fit a Gaussian to the color distribution of all stars in A1 with absolute magnitudes in the range $3 < M < 33$. The peak of the distribution lies at $(V-I)_0 = 1.53$ which we adopt as the dereddened value of the color index, $(V-I)_0^{35}$. Figure 8 shows the result of comparing $(V-I)_0^{35}$, which is the dashed line, with theoretical values extracted from the RGB bol of the Girardi et al. isochrones which are displayed as solid lines. The dotted lines represent the 1 $\sigma$ width of the observed distribution. Interpolating between the theoretical lines by eye we estimate that the bulk of the RGB stars in A1 could have metallicities in the range $1.3 < [M/H] < 0.8$ at an age of 14.1 Gyr and $0.8 < [M/H] < 0.4$ at 2 Gyr. These two ages are, respectively, the approximate maximum and minimum possible ages for the most luminous RGB stars and are constrained by the age of the Universe and the time at which the RGB phase transition occurs (Ferraro et al. 1995; Barker et al. 2004). In A2 the consistent ranges are $1.7 < [M/H] < 0.8$ at 14.1 Gyr and $1.1 < [M/H] < 0.4$ at 2 Gyr. These are not enough stars in A3 to reliably fit a Gaussian using the same procedure. These limits are very approximate as we have only used the central 68% of the RGB stars. In addition, the presence of AGB stars could cause an underestimate of the metallicity because they lie just to the left of the RGB stars of the same age and metallicity. We have also only used a small portion of the RGB whose overall shape depends on chemical composition and age. Paper III has a more thorough analysis which includes these effects.

The color and magnitude of the RC are also sensitive to the age and metallicity of its constituent stars. In Figure 9 we show a close-up of the RC region in A1 with mean theoretical values from Girardi & Salaris (2001) as a function of metallicity and age. The curves have global metallicities of 1.3, 0.7, and 0.4 from left to right, respectively. The open circles correspond to 1 Gyr, squares to 2 Gyr, triangles to 5 Gyr, stars to 8 Gyr, and filled circles to 12 Gyr. The cross marks the observed mean magnitude and color of the RC.
Fig. 10. CMD of A1 with the RGB ridge lines and HB loci of M 92 ([Fe/H] = 2.54), NGC 6752 ([Fe/H] = 1.54), and 47 Tuc ([Fe/H] = 0.70) overplotted.

= 154 (NGC 6752) and 0.70 (47 Tuc). This empirical comparison is in agreement with what we found above using the Girardi et al. models and demonstrates that no serious errors have been introduced in the transformation to the ground-based system.

The HB loci of the same three GGCs are also plotted in Fig. 10. Stars in the blue HB tail at (V - I) 0 belong to both M 92 and NGC 6752 while the red HB at (V - I) 0.9 belongs to 47 Tuc. The bulk of M 33’s core helium burning stars are brighter than those of 47 Tuc providing further evidence for a population younger than the GGCs. However, as noted previously, the faintest portion of M 33’s RC could contain stars as old as 47 Tuc. Because of its magnitude and color range, the young M S makes it difficult to confirm or rule out completely the presence of a blue HB tail in M 33 similar to that of M 92. However, it appears that any such population is likely to be a small fraction of the total core helium burning population at the present epoch since there is no significant overdensity of stars on the MS as would be expected from such a feature superposed on the MS. There are some stars located in the Hertzsprung Gap between the MS and RC which could be blue HB stars, sub-giant branch (SGB) stars, 1 Gyr old, or foreground stars.

Figures 11-13 display the CMDs for the three W FPC2 fields. Due to the shorter exposure time in F606W, the limiting magnitude is about 2 mag brighter than the ACS fields. Most of the CMD features are washed out except for the RGB. Because of the shallower photometric depth and fewer number of stars, we do not use the W FPC2 CMDs in any part of this study except in the analysis of stellar surface density.

4. Stellar Surface Density

The spatial distribution of stars can yield insight into what type of population we are observing (i.e., disk, thick-disk, or halo). We show the surface density of RGB stars as a function of deprojected radius in Figure 14. The stars were selected to lie between the lines in Figs. 11–13 (note that the lines are not shown in Figs. 4–6 for clarity). Each ACS field was divided into four radial bins (represented by diamonds) whereas each W FPC2 eld was treated in its entirety (represented by squares). Since W 1 coincides with A 3, the W FPC2 elds were brought onto the completeness scale of the ACS elds by normalizing the surface density in W 1 to that in A 3. This avoids making uncertain estimates of the differing completeness rates between the ACS and W FPC2 elds within the RGB selection region. However, using the raw W FPC2 completeness does not change the results. Hence, W 1 is not shown in Fig. 14 nor is it included in the ts below. The error bars reflect the Poisson uncertainty normalized by the actual area observed in each radial bin.

Note that we have neglected error bars in deprojected radius due to the finite thickness of the disk. Seth et al. (2005) observed a sample of edge-on late-type spiral galaxies similar to M 33 and found the vertical scale heights of their RGB stars to range from 200 – 700 pc. If we take 500 pc as representative, then this translates
to an uncertainty of $0.74 \text{kpc}$ for M 33. We have also assumed that the inclination and position angle are constant. Corbelli & Schneider (1997) took a tilted-ring model to the H I distribution and found that the position angle changes from $+20$ to $15$ over the region we have observed. Whether the stellar disk follows this change is unclear.

An exponential profile was fit to the observed distribution in a least-squares sense and it is shown as the dotted line in Fig. 13. The scale length of the $t$ is $4.9^0 \pm 0.4^0$. The surface density in W 3 shows a significant $3\sigma$ deviation from the exponential profile. To assess the level of contamination from background galaxies and foreground stars we reduced a subsample of im ages (2 in each l ter) of the Hubble Deep Field using the same technique and thresholds that were applied to M 33. The resulting CMD is shown in Figure 15 and contains 7 objects in the RGB selection region. Therefore, we estimate the surface density of background galaxies and foreground stars to be $1 \text{arcmin}^{-2}$. Including this constant $c$ set in the $t$ reduces the exponential scale length to $4.7^0 \pm 0.5^0$.

The solid line in Fig. 14 represents the sum of the exponential (dashed) and $c$ set (dot-dashed). The last point still shows an excess of stars but only at the $1.8\sigma$ level. If this excess is not due to Poissonian variations then it could represent a transition to a more extended stellar component, a point to which we return later.

The K-band surface brightness scale length of M 33 has been measured to be $5.8^0 \pm 0.9^0$ (Regan & Vogel 1994; Simon et al. 2006). When dealing with integrated light, the K-band is generally thought to be a better tracer of the stellar distribution than optical bands (but see Seth et al. 2005 for an alternative view). Regan & Vogel found a systematic decrease in the surface brightness scale length with wavelength. They used a simple toy model which ascribed this trend to the absorbing $e$ $e$ $e$s of dust. Their model neglected the effects of forward scattering and variations in stellar age and abundance but predicted that the true scale length of the stellar disk is $5.3^0$.

Our estimate of the scale length is a more direct measurement of the underlying stellar structure and is free from many of the systematic uncertainties arising from the geometry of the dust in regions outside that studied by Regan & Vogel and Simon et al. Hence, if M 33’s density profile is not a single exponential then the differences between our measurements and theirs would be expected. Rowe et al. (2005) surveyed M 33’s luminous stellar populations and found a clear break in the carbon star profile at $R_{dp} \approx 35^0$. While they did not make any exponential fits to their profile we estimate by eye that outside this radius the scale length of their profile is remarkably close to our result. This picture is confirmed by Ferguson et al. (2006) who conducted a wide-field survey of M 33 with the INT 2.5-m
Fig. 16. CMD of A1 and the six boxes used to study the age dependence of the radial scale length.

Fig. 17. Relative surface density of stars in each box shown in Fig. 16.

telescope. They reported a similar break in the RGB density profile at about the same radius found by Rowe et al. and beyond which the scale length is similar to what we have found.

In Paper I, we found that massive MS stars were more concentrated toward M 33’s nucleus than AGB stars which in turn were more concentrated than RGB stars. This implies a progression in the stellar scale length with age. Inspection of the CMDs presented here also suggests that the density of stars in the young MS declines faster than the density of RGB stars. To investigate this in more detail we selected several regions of the CMD on the basis that each region probes a different age range. Using the results of Paper III we found that contours of constant age run roughly diagonally since the main sequence turnoff and sub-giant branch move toward fainter and redder magnitudes with age. Figure 16 shows the regions we selected. The boundaries were chosen to roughly follow lines of constant age and the sizes were chosen as a compromise between the need for good number statistics and a small range of ages in each box. The faint limit was chosen to avoid the region where systematic magnitude errors dominate and to minimize contamination from non-stellar sources. Gallart et al. (1999) used a similar approach to isolate different age ranges in studying the star formation history of Leo I. Table 2 lists the mean age (averaged over all three fields) and scale length for each box and their standard deviations.

In Figure 17 we show the relative stellar surface density of each box for fields A1-A3. There is a trend of decreasing concentration as the boxes get fainter, and, hence, older. We fit an exponential profile to each box’s stellar distribution spanning all three fields. Figure 18 displays the behavior of the scale length with mean age. The curved lines show three power-law relations of the form $h = 3t$ with $t = 0.1; 0.3; 0.5$. The form of these relations is somewhat arbitrary and we show the curves only for reference. The vertical error bars are the statistical uncertainties in the scale length from the least-squares fitting procedure. The horizontal error bars represent the spread of the ages in each box. The precise ages probably represent the largest source of uncertainty in this plot. The y-errors are fairly uniform but the x-errors increase dramatically for the oldest boxes. This is because the stellar isochrones get more photometrically

TABLE 2

| Box | Age (Gyr) | h (arc min) |
|-----|-----------|-------------|
| 1   | 0.35      | 0.15        | 1.92 | 0.22 |
| 2   | 0.62      | 0.58        | 2.98 | 0.27 |
| 3   | 1.90      | 1.79        | 3.55 | 0.18 |
| 4   | 4.31      | 3.00        | 4.09 | 0.14 |
| 5   | 6.02      | 3.40        | 4.56 | 0.14 |
| 6   | 6.79      | 3.45        | 4.86 | 0.18 |

Fig. 18. Disk scale length as a function of age. Each point and horizontal error bar is the mean and standard deviation of stellar ages for each box shown in Fig. 14. The vertical error bars are the random uncertainties in the scale lengths from the least-squares fits. Three arbitrary power-law relations where $h = 3t$ are shown for comparison.
degenerate with age. Comparison of the power-law relations suggests that \( 0.1 \) . . . . 0.3 but we refrain from making a more precise estimation due to the inherent systematics uncertainties. We discuss possible interpretations in Section 5.

5. Metallicity Distribution Functions

Following the analysis in Paper I, we employ the Saviæne et al. (2000) grid of RGB models to construct the metallicity distribution function (MDF) of each eld. Those authors used a large homogeneous photometric database of GCs to derive a function which has one parameter, [Fe/H], that specifies the shape of the RGB. If an RGB star's absolute magnitude and reddened color are known, then the function can be solved for the star's metallicity. To minimize contamination from foreground stars, AGB stars, and red supergiants, we restrict the present analysis to stars in the region 1.0 \((V - I)_0 \) 2.2 and 3.9 \(M_\odot \) 24. The total number of stars in the selected CMD region is 207 in A1, 84 in A2, and 34 in A3.

The resulting MDFs for A1, A2, and A3 are displayed in Figure 19 as the solid-line generalized histograms from top to bottom, respectively. These were constructed by assigning a unit Gaussian to each star with a standard deviation equal to the star's metallicity uncertainty. The median metallicity is 1.14, 1.23, and 1.30 while the interquartile range is 0.4, 0.6, and 0.6 dex. The dashed line represents the instrument metal response, namely the recovered distribution for a test population having a single metallicity (Belazzini et al. 2002a). The test population consisted of 2000 stars whose input magnitudes reproduced the observed RGB luminosity function and whose colors reproduced the Saviæne et al. RGB ridge line for [Fe/H] = 1.1. The standard deviation of the recovered distribution is 0.04 dex and represents the total intrinsic random error introduced during the entire measuring process from the photometric reduction to the measurement of metallicity. We note that when the 1 uncertainties in the distance and reddening are added in quadrature they introduce a systematic error of 0.1 dex.

6. Metallicity Gradient

We are interested in tracing out the extent of M 33's disk. To do so we must place the results of the previous section in the context of other studies. We have culled from the literature a list of RGB metallicity measurements in M 33 using similar techniques. Figure 23 summarizes these measurements. The open triangle is based on the results of Stephens & Frogel (2002, SF02) who imaged the central 22° of M 33 with Gemini North. They obtained near-IR photometry and from the slope of the RGB calculated a mean metallicity of 0.26 \(M_\odot \) 0.27(dan). The filled circles are the results of Kim et al. (2006), who obtained VI photometry of 10 W FPC2 elds located throughout the disk \(R_{dp} 1.6 \) kpc. They found median metallicities ranging from 0.6 to 0.9 with a typical error of 0.09 dex. It is not clear whether their quoted errors are random or systematic. The open circles correspond to the results of Galliet et al. (2004, G04), who obtained VI photometry of two elds in the NW of M 33's nucleus. In both elds they found a median metallicity of 1.03 \(M_\odot \) 0.40 where the error represents the instrument metal response. The filled squares are the results of Paper I (PI) after applying a missing factor of \(\cos(\theta, \phi)\) in the original calculation of deprojected radii. The error bars denote the systematic uncertainties. A large survey covering projected radii of 26° \(R_{dp} 60 \) was conducted by Brooks et al. (2004, B04) who found a peak metallicity of 1.27 \(M_\odot \) 0.04 (rand) which is shown as the open (downward-pointing) triangle. Davidge (2003, D03) imaged a eld at \(R_{dp} 72 \) and found evidence for an excess number of stars relative to a control eld which he interpreted as AGB and RGB stars in M 33. He measured the RGB metallicity to be [Fe/H] = 1.0 \(M_\odot \) 0.3 (rand) \(M_\odot \) 0.3 (sys) which is shown as an open square. We show only the random error to be more consistent with the other points. The filled triangles represent the results of the present study while the errors are the instrument metal responses discussed in the previous section.

The star symbols in Fig. 20 correspond to 9 halo globular clusters of M 33. Their metallicities were estimated by Sarajedini et al. (2000, S00) using W FPC2 V I photometry and the slopes of the cluster RGBs. The errors for the clusters are random errors propagated through the relations between RGB color, slope, and metallicity. The mean metallicity of these clusters is 1.27 \(M_\odot \) 0.11 (rand). Recently, Sarajedini et al. (2006) studied the RR Lyrae (RRL) population in an ACS eld located at \(R_{dp} 15 \). They found that the RRL metallicity distribution exhibited a pronounced peak at [Fe/H] = 1.3 which they interpreted as evidence for a halo population. The dashed line in Fig. 20 therefore represents the halo of M 33 (including clusters and eld stars).

M 33's disk presumably has a different star formation history from its halo so a transition from one to the other could be observable as a change in the apparent RGB metallicity gradient. The dotted line in Fig. 20 is the transition inward on elds (filled circles) from K02 while the solid line is the same eld which excluded the innermost two elds where crowding was severe. We stress that these elds were made independent of the other metallicity measurements. In Paper I, we found that the metallicity...
Fig. 20. RGB metallicity gradient in M 33. The dotted and solid lines are, respectively, the fits from K02 to all the red circles and all but the inner two where crowding was severe. The dashed line represents M 33’s halo metallicity (see text for details).

ity gradient was consistent with the inner disk gradient. In the present study we find that the same gradient extends out to $R_{dp} = 50'$. Past this radius there appears to be a flattening in the gradient but the situation is somewhat uncertain. B04 interpreted their eld to be dominated by a halo population because the shallow surface density profile with a power-law slope of $1.47$ and because their metallicity matched the globular clusters. Whereas, D03 suggested the asymptotic giant branch and RGB stars he found were the old counterparts to the globular clusters which may have formed over a time scale of several Gyr (see also S00). Unfortunately, these analyses relied heavily upon the adopted level of contamination from foreground Galactic stars and background galaxies. Only more precise measurements of RGB metallicities at radii past $R_{dp} = 60'$ could determe if the disk gradient continues outward or if the slope attains an $I_{min}$ might be expected for a halo (or thick-disk) population. Such measurements could require large areas to obtain a statistically significant sample of RGB stars.

Finally, there are several important considerations to note while examining Fig. 20. First, we have used our ducial M 33 distance, inclination, and position angle and the centers of the elds studied to determine their deprojected distances. Because the D03, B04, and G04 elds were relatively large, it would be more accurate to plot their positions according to the mean RA and DEC of the RGB stars in their elds. Depending on the geometry of their elds relative to M 33’s nucleus, this could have the effect of moving them inward to smaller radii because of the negative stellar density gradient.

Most importantly, all of the measurements presented in Fig. 20 compared M 33’s RGB stars to the GGCs which are old (> 12 Gyr) and contain enhancements in the $\alpha$-element abundance ([$Fe/H$] > 0.3). As pointed out by Salaris & Girardi (2005), the RGBs of galaxies with composite stellar populations, such as the LMC and SMC, are often dominated by stars signi cantly younger than the GGCs with [Fe/H] < 0.0. Hence, the metallicities of such systems derived using the GGCs as ducials could be underestimated by several tenths of a dex. Indeed, in Paper III we model the star formation history of elds A1 A3 using stellar evolutionary tracks with [Fe/H] = 0.0 and we nd that the true metallicity is 0.4 dex higher but the metallicity gradient through the elds is roughly unchanged. From the Girardi et al. isochrones we estimate that approximately half of this offset is due to the lower $\alpha$-element abundance and half is due to a younger mean age (6 8 Gyr). If the outer regions were as young as 2 Gyr, the total offset would amount to 0.5 dex. Currently there is no information on the star formation history of M 33’s inner disk so it is possible the RGB metallicity gradient over its entire disk is shallower or steeper. However, it is unlikely that an age gradient can mimic the apparent metallicity difference of 0.8 dex between M 33’s central and outer regions because the latter are not young enough.

7. DISCUSSION

It has been observed that many spiral galaxies exhibit a sharp drop in star formation across their disks, as measured by the surface brightness of the H $\alpha$ recombination line. The location of this drop, $R$, often occurs close to where the gas surface density falls below a theoretically determined critical density required for star formation. The nature and dependence of this threshold density on the local environment is not exactly clear. Kennicutt (1989) and Martin & Kennicutt (2001) argue that it is governed by gravitational instability as parametrized by the Toomre Q parameter. This parameter depends on the local epicyclic frequency and gas velocity dispersion. It accurately predicts the critical radius for many high surface brightness galaxies but fails for some low-mass spirals like M 33 ($R = 29'$) where large portions of
the disk are below the threshold gas density but actively
forming stars.

Corbelli (2003) used measurements of the gas kine-
matics in M 33 to derive an extensive rotation curve and
mass model. She found that the Toomre criterion could
correctly predict R in M 33 if the surface density of ei-
ther the stellar disk or dark matter was added to the gas
density. Alternatively, a stability criterion based on the
shear rate with a low gas velocity dispersion could also
correctly predict R. However, such a model criterion
does not work as well for most other galaxies (Martin &
Kennicutt 2001).

What implications do our results have for the star for-
mation threshold in M 33? We noted in that eld A1
contains stars 3.5 M while A2 and A3 contain stars
3.4 M. These massive stars can be no older than their
MS lifetimes of 100 400 Myr and unless we have coincidentally observed them at the end
of their MS phases then they are probably even younger.
This fact is direct evidence for recent star formation at
R 35° 50° in apparent disagreement with M 33’s
star formation threshold radius of 29°. It is possible
that these massive stars actually formed at smaller radii
and have since migrated outward. Given their young ages,
however, there probably has not been sufficient time
for this to occur.

Could star formation be ongoing today in our elds?
Boissier et al. (2006) used GALEX images to study the
radial variation of star formation in 43 spiral galaxies.
Included in their sample was M 33 whose far-UV pro-
le is extended out to R 43°, well past the threshold radius
measured with H. Indeed, nearly all of the galaxies in
their sample displayed similar behavior leading to the
conclusion that star formation is ongoing today in the
outskirts of these galaxies but at levels too low to pro-
duce any ionizing stars. The UV continuum, however,
is sensitive to the star formation rate integrated over the
last 100 Myr. In contrast, the H observations trace the
star formation rate over the last 20 Myr (Kennicutt
1998). Therefore, it is possible that there are no ionizing
stars alive today because star formation ended 20 100
Myr ago.

This latter scenario could explain our observations of
young stars in M 33’s outskirts beyond the H thresh-
old radius and, therefore, save the applicability of the
Toomre Q param for M 33. However, we would still
need to explain how star formation could have occurred
at all so recently despite the low gas densities in these
regions. Was the disk density in the recent past above
the threshold density? To answer this we need to know
the current densities of the gas, stars, and dark matter.

A according to the tilted-ring model of Corbelli (2003)
the azimuthally averaged HI column density is 30,
20, and 15 M pc at the central radii of elds A1, A2, and A3, respectively. Complexities in the HI distri-
bution can cause systematic and random errors when
performing azimuthally average data even in detailed tilted-
ing models. Such is the case in M 33’s outer disk where
residuals between the model and observed ux at dif-
erent position angles within a ring can vary by a factor
of 2 (Corbelli & Schneider 1997). An azimuthally aver-
aged column density is what are commonly reported
in the literature for other galaxies so we use them here
as well. The high resolution aperture synthesis map of
Newton (1980) shows that the H I density throughout our
elds is below the lowest contour which corresponds to
43 M pc .

The amount of molecular gas in our elds is di-cult
to ascertain but is unlikely to contribute signi-
cantly to the total gas content. Our elds lie outside the GMC
survey of Engargiola et al. (2003) and are at the hi-
mit of the sensitivity and coverage of the CO maps presented
by Heyer et al. (2004). The outer most reliable point in
their map is at R 24° where the H I column density
is 1 M pc . This can be taken as a rough upper
limit for our elds considering that the CO to H I
conversion factor may be di-e rent in the outer disk where
the metallicity is lower.

A crucial point to consider is whether the gas density
in our elds could have been signi cantly greater just a
couple hundred Myr ago. This possibility is actually ruled
out by the low star formation rate required to explain
the small number of young, massive stars observed. From
the star formation histories calculated in Paper III we find
that the mean star formation rate in the past 400 Myr
has been <0.04 M pc Gyr . Thus, no more than
0.02 M pc could have been converted to stars in that
time.

Corbelli (2003) calculated the variation in the thresh-
old density with radius in M 33. According to her plots,
the Toomre Q criterion predicts a threshold disk density
that drops from 7 to 6 M pc across elds A1 A3
whereas the shear rate criterion predicts a threshold that
is approximately constant at 5 M pc . Therefore, a
few hundred Myr ago the gas density was below either
threshold. Corbelli’s mass model predicts the gas to
dominate the baryonic mass in these outer regions so
it is also unlikely that the stellar mass contributes signi-
cantly to the total disk surface density. On the other
hand, the dark matter density within the disk is about
equal to the gas density. Hence, including dark matter
in the total disk density can explain the recent star for-
mation in eld A1 but not A2 or A3.

A growing body of evidence has suggested that a con-
stant threshold gas density of 3 10 M pc describes
the extent of star forming disks equally well if not better
than a radiating varying threshold like the Toomre Q pa-
rameter or shear rate criterion (Skillman 1987; Taylor
et al. 1994; Ferguson et al. 1998; Martin & Kennicutt
2001). The physical basis for such a threshold could be
related to the minimum pressure needed for the for-
ation of a cold gas phase in the ISM (Elmegreen & Parravano
1994, Schaye 2004). If such a constant threshold applies
to M 33 then our results imply it is . 3 M pc
and could be as small as 1 M pc . Indeed, Boissier et al.
(2006) trace M 33’s far-UV pro-duction out to gas densities
of 1 2 M pc .

We now return to our nding that the stellar scale
length increases with age. This result raises several in-
teresting questions. Does this effect something funda-
mental about M 33’s collapse history? Does it arise from
the progression of star formation on galactic scales? Or is
it a by-product of subsequent dynamical processes which
act to redistribute stars after they are formed?

In the con mon picture of inside-out galaxy for-
mation the scale length of all stars and stellar rem-
nants increases as the disk builds up to the present day size (e.g. Naab
This means that the oldest stars we observe today should have the smallest scale length in contrast to our results which show the opposite trend in M 33. This seems to suggest an outside-in formation scenario.

A different interpretation is that we are observing a transition between two distinct components in M 33, like a disk/thick-disk or disk/halo. This would explain why the number of RGB stars in the outer halo is larger than predicted by a simple exponential plus constant model. If this is correct, then the A 2 halo could have a non-negligible thick-disk/halo component which might explain why its metallicity is close to that of M 33's halo. Interestingly, the M-star problem measured by Row et al. (2005) shows a flattening at approximately the same location as the A 2 A 3 further hinting at a second, more extended component.

M 33's halo was recently isolated kinematically by M o'Connell et al. (2006) who analyzed Keck D E M O S spectroscopy of 280 stars located 38° along the major axis. These authors found evidence for three distinct kinematic components: a disk, halo, and an intermediate component which they hypothesized could be tidal streams in M 33. It is unclear how the intermediate component would affect our results because, if it is a stream, it might not pass through our fields. The halo component, however, would be present in our fields although its precise contribution is uncertain. Our fields lack at about the same disk-projected distance as those observed by M o'Connell et al. but they are on the minor axis so the halo-to-disk ratio could be larger depending on the true halo density distribution.

Creating the picture is the possibility of disk orbital heating mechanisms. These processes must, at some level, modify the stellar age, metallicity, and density gradients put in place by star formation regardless of whether it progresses inside-out or vice-versa. (e.g., Lepine et al. 2003, Sellwood & Binney 2002, W jelen et al. 1996). The classical mechanism involves gravitational encounters between stars and giant molecular clouds of mass $10^6$ M$_\odot$ (Spitzer & Schwarzschild 1953). This process has been shown to heat the stellar disk at a rate where the vertical and radial velocity dispersions are related by $\sigma_z / \sigma_R = 0.25$ and $\sigma_z = 0.7$ (Lacey 1984, Kimm sen 1985). Unfortunately, observations in the Galaxy indicate that 1) there are too few GMCs with the requisite mass (Lacey 1984), 2) 0.5 $\pm$ 0.5 (W jelen 1977), and 3) $\sigma_z = 0.5$ (Hanninen & Flynn 2002). In response, other mechanisms have been proposed, from heating by spiral arms to massive halo black holes passing through the disk (Lacey & Ostriker 1985). The formation process in spiral galaxies like M 33 (Seth et al. 2005). We are unable to say whether this behavior is due to the orbital di usion of stars as they age or to intrinsic variations in star formation history with radius.

Given the exponential radial distribution, metallicity gradient, and fixed ages present in our fields it is likely they belong predominantly to M 33's disk. This would mean that M 33's disk extends out to at least R$_{200}$ or 6 V-band scale lengths. However, we cannot rule out the presence of a small, extended component like a thick-disk or halo in the outermost field. This possibility can be tested with kinematics by extending the metallicity measurements in M 33 beyond this region to see if its gradient changes.

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8. Conclusions

We have presented deep V I photometry of three fields in M 33's outskirts at deprojected radii of 4 6 V-band scale lengths. The CMDs reveal a fixed stellar population with ages ranging from 100 M yr to at least several Gyr. The presence of such young stars so far out in this galaxy is consistent with a low global star formation threshold. Assuming our fields are representative of all position angles at similar deprojected radii in M 33, we argue that the threshold cannot be signiﬁcantly more than the present-day azimuthally averaged gas surface density of $10^3$ M pc$^{-2}$. This behavior is similar to what we have found in M 33 for the radial direction and point to a common origin in all late-type spirals.
