CARBON STARS AND OTHER LUMINOUS STELLAR POPULATIONS IN M33

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ABSTRACT

The M33 galaxy is a nearby, relatively metal-poor, late-type spiral. Its proximity and almost face-on inclination means that it projects over a large area on the sky, making it an ideal candidate for wide-field CCD mosaic imaging. Photometry was obtained for more than 10⁶ stars covering a 74′ × 56′ field centered on M33. Main-sequence, supergiant branch, red giant branch, and asymptotic giant branch (AGB) populations are identified and classified based on broadband V and I photometry. Narrowband filters are used to measure spectral features allowing the AGB population to be further divided into C and M star types. The galactic structure of M33 is examined using star counts, color-color–, and color-magnitude–selected stellar populations. We use the C to M star ratio to investigate the metallicity gradient in the disk of M33. The C/M star ratio is found to increase and then flatten with increasing galactocentric radius, in agreement with viscous disk formation models. The C star luminosity function is found to be similar to M31 and the SMC, suggesting that C stars should be useful distance indicators. The “spectacular arcs of carbon stars” in M33 postulated recently by Block et al. are found in our work to be simply an extension of M33’s disk.

Key words: galaxies: individual (M33) — galaxies: stellar content — stars: carbon

Online material: color figures, machine-readable table

1. INTRODUCTION

Carbon star (C star) production is caused when deep stellar convection dredges up material created by nuclear fusion processes. Whether a star is a C or an M star depends on the C/O ratio in its photosphere. If a star is formed from initially metal-poor material in the original protostellar cloud, then less carbon is required to alter the surface chemistry from oxygen dominated (C/O < 1) to carbon dominated (C/O > 1). Photospheric chemistry is dominated by the production of CO molecules. An overabundance of carbon leads to molecules such as CN being formed, whereas an overabundance of oxygen leads to production of molecules such as TiO. An asymptotic giant branch (AGB) star initially has an oxygen-dominated photosphere, inhibiting the formation of CN, as any carbon primarily forms CO. When a star undergoes dredge-up, carbon-rich material mixes into the photosphere. If there is initially a low oxygen abundance in the star, then little carbon is needed to transform it from an M star into a C star. Thus, the ratio of the number of C stars to M stars will depend on the initial metallicity of the system, and observations support the idea that higher C/M ratios occur in lower metallicity systems and galaxies (Blanco & McCarthy 1983; Richer et al. 1985a; Cook et al. 1986; Mould & Aaronson 1986; Aaronson & Olszewski 1987; Brewer et al. 1995; Albert et al. 2000). The observed correlation spans 4 dex in C/M and 1.5 dex in [Fe/H] (Groenewegen 2002) and holds regardless of the galaxy morphology or star formation history. This provides a method to measure the metallicity distribution within a galaxy, as only age and metallicity appear to have a strong effect on the C/M star ratio.

Located in the Triangulum constellation, M33, also known as the Triangulum galaxy, is a late-type spiral located approximately 840 kpc away. A V-band image using data from this work is shown in Figure 1. M33 is substantially smaller in size and mass than both M31 and the Milky Way and is an interesting target to study, as its AGB/red giant branch (RGB) stellar content is easily resolved in 4 m class telescopes. In contrast to M31, M33’s lack of nearby dwarf companions provides it with an almost isolated environment.

AGB stars are members of intermediate-age (1–10 Gyr) stellar populations and represent a relaxed subsystem in galaxies (Nowotny et al. 2001). This means that AGB stars uniquely record the star formation history of the galaxy at intermediate ages, as well as sampling its history of minor mergers. By observing M33 to large galactocentric distances, we can examine the underlying stellar population to see if there is evidence for recent tidal interactions. For example, the newly discovered tidal ring that appears to surround the Milky Way was identified through observations of an F star overabundance (Newberg et al. 2002; Ibata et al. 2003). Using the C/M star ratio one can trace metallicity variations in a galaxy. Zaritsky’s (1992) star-forming viscous disk models predict a change in the slope of the metallicity gradient at the radius where the rotation curve flattens. The current data set allows us to measure the metallicity gradient of M33 as a function of galactocentric radius, thus allowing tests of galaxy formation and evolution models to be made.

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1.1. C Star Classification

To distinguish C- and M-type AGB stars, groups led by Richer (Richer et al. 1984, 1985a, 1990; Richer & Crabtree 1985b; Pritchet et al. 1987; Hudon et al. 1989) and Aaronson (Aaronson et al. 1984, Cook et al. 1986) developed a four-band photometric system (FBPS) to classify AGB stars. The FBPS uses two narrowband filters to provide low-resolution spectral information and two broadband filters for temperature information. The filters used are listed in Table 1. A C star spectrum will have CN bands, whereas an M star is dominated by oxide bands, such as $\text{H}_2\text{O}$ and TiO. The CN and TiO filters were developed to measure the CN and TiO molecular band strengths. Figure 11 of Brewer et al. (1996) illustrates spectra of a C star, an M star, and an A star, and demonstrates how the filters easily discriminate between the three. A C star will have strong absorption in the CN filter and, when compared with the magnitude measured in TiO, will produce a positive CN/C0 TiO index. An M star will produce a negative CN/C0 TiO index, as it will exhibit strong absorption from TiO. An A star will produce a CN/C0 TiO index of approximately zero. In the study of Brewer et al. (1996) the validity of the system was confirmed by spectroscopic observations.

The FBPS allows large areas to be quickly surveyed by direct imaging, providing simultaneous measurements of all stars in the field of view. This is in contrast to spectroscopic observations, which are limited to a relatively narrow field of view, small numbers of potential targets, and longer integration times. The FBPS is also advantageous because it works in fields too crowded for grisms. Spectroscopic survey strategies applied to the LMC (Blanco et al. 1980; Blanco & McCarthy 1983) would not work in the present case on account of the faintness and crowding of M33’s stars. A spectroscopic survey of all potential AGB stars in M33 for the purpose of classification is unfeasible. Using the FBPS, stars can be quickly classified and targeted for follow-up spectroscopic studies.

2. OBSERVATIONS

Multiband photometric data were collected on 1999 October 30 and 31 and 2000 December 3 and 4 with the 3.58 m Canada-France-Hawaii Telescope (CFHT). The detector used was the CFH12k mosaic CCD camera, which employs 12 MIT/LL CCID20 CCDs to provide an effective size of 12 228 ; 8192 pixels. The camera is positioned at prime focus, has a pixel size of 15%/22, a plate scale of 0%/206 pixel1, and a 42'0; 28'0 field of view (approximately 1.5 times the size of the full Moon). The centers of the four fields in M33 that were observed are listed in Table 2. The total observed area covered by the four fields is 80'0; 50'0. An observing log is given in Table 3.

3. DATA REDUCTION

The science images required correction of bad pixels, over-scan and bias subtraction, and flat fielding. These operations were completed using the mscred package in IRAF.2

![Fig. 1.—M33 mosaic V-band image constructed from the CFHT images and covering the entire area of the present survey.](image)

### TABLE 1

| Filter | Central Wavelength (nm) | Bandwidth (nm) | Maximum Transmission (%) |
|--------|-------------------------|----------------|--------------------------|
| Mould V | 537.4 | 97.4 | 94 |
| Mould I | 822.3 | 216.4 | 91 |
| TiO | 777.7 | 18.4 | 92 |
| CN | 812.0 | 16.1 | 95 |

**Note.**—Col. (1): filter; cols. (2) and (3): central wavelength in nanometers; col. (4): maximum transmission as a percentage.

### TABLE 2

| Field ID (1) | R.A. (2) | Decl. (3) |
|--------------|----------|----------|
| M33-1 | 135 24 | +31 06 30 |
| M33-2 | 132 18 | +31 06 30 |
| M33-3 | 135 23 | +30 39 30 |
| M33-4 | 132 18 | +30 39 30 |

**Note.**—Col. (1): field ID; cols. (2) and (3): R.A. and decl. in J2000 coordinates. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

2 The Image Reduction and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
3.2. Broadband Data Processing

The flat fields for the broadband data set suffer from a strong, variable, scattered light pattern. Flat fielding with these images introduced a 20% response error as a smooth gradient. The scattered light signal was also found to dramatically change with each flat-field image. This effect meant that when the images were averaged together, $\sigma$-clip routines to remove stars failed, as it was impossible to scale each image to a uniform level so that deviant pixel values could be reliably removed. To fix this problem each flat-field image was heavily smoothed with a $500 \times 20$ boxcar filter, leaving behind the slowly varying background. Subtracting this signal from the original flat-field image leaves an image containing the pixel-to-pixel sensitivity changes and objects such as stars and cosmic rays. A bad-pixel mask was used to identify and correct the defects with interpolation from nearby pixels.

The residual images from subtracting the smoothed flat-field images were averaged using a $\sigma$-clipping algorithm to reject pixels affected by stars or cosmic rays. This flat-field–corrected pixel-to-pixel sensitivity differences but failed to remove the overall gradient. This instrumental signature was removed by using the science images themselves. It was assumed that the individual CCD fields on the mosaic, which were farthest from the center of the galaxy and hence least contaminated by stars, should be completely flat. The assumption of intrinsic flatness is justified, as according to the NASA Extragalactic Database (NED), M33 reaches 25 mag arcsec$^{-2}$ in the $B$ filter at a major axis radius of 70.8. The ratio of the major axis to the minor axis

| Date          | Target | Filter | Exposure (s) | FWHM (arcsec) | Air Mass |
|---------------|--------|--------|--------------|---------------|----------|
| 1999 Oct 30   | M33-3  | $V$    | $3 \times 400$ | 0.7, 0.7, 0.7 | 1.20, 1.18, 1.16 |
| 1999 Oct 31   | Sky flat | $V$ 30, 21, 15, 6, 5, 4 | ... ...
| 2000 Dec 3    | M33-3  | TiO $3 \times 1000$ | 0.6, 0.6, 0.6 | 1.07, 1.05, 1.04 |
| 2000 Dec 4    | Sky flat | CN 6 x 5.7 | ... ...
|               | Sky flat | TiO $2 \times 12, 2 \times 20, 30$ | ... ...
|               | Sky flat | CN 40, 60, 100, 140, 200 | ... ...

Note.—Col. (1): date of the observation; col. (2): target or type of calibration image; col. (3): filter used; col. (4): number of exposures and exposure time in seconds; col. (5): average FWHM of stars on each frame in arcseconds; and col. (6): air mass for mid-exposure.

Much of the CFH12k is free of defects, such as bad columns and hot pixels, but some CCDs show significant cosmetic flaws. This includes CCD05 for which approximately 30% of the CCD pixels are defective. Defective regions often show a nonlinear response to the number of incident photons. For CFH12k, the number of ADUs per pixel at which nonlinearity becomes significant is different for each CCD and ranges from 51k to 65k. Bad pixels and columns can be treated in two ways. The first is to ignore them in the reduction; the second is to interpolate over these pixels using surrounding pixels. The general approach taken in this work is to simply ignore bad pixels, especially since the images are dithered, so chances are good that every part of the target will be observed at least once. Only in very specific cases do we apply a correction to bad pixels, which we describe in § 3.2. The broadband data (obtained in 1999 October) and narrowband data (obtained in 2000 December) were reduced in different ways, as described below.

3.1. Narrowband Data Processing

After bias corrections, gain differences across the CCD were corrected for by combining twilight flats for each filter. When combining frames, a 3 $\sigma$-clipping criterion (in mscred.combine) is used to eliminate high and low pixel values. This works well for the sharp bright centers of stars’ PSFs, but the extended wings are too faint to be excluded. To overcome this problem, a star’s PSF is used as a tracer to reject all pixels within a specified radius. For CFH12k, a radius of 15 pixels was found to work well from visual examination of the images.

3.2. Broadband Data Processing

The flat fields for the broadband data set suffer from a strong, variable, scattered light pattern. Flat fielding with these images introduced a 20% response error as a smooth gradient. The scattered light signal was also found to dramatically change with each flat-field image. This effect meant that when the images were averaged together, $\sigma$-clip routines to remove stars failed, as it was impossible to scale each image to a uniform level so that deviant pixel values could be reliably removed. To fix this problem each flat-field image was heavily smoothed with a $500 \times 500$ pixel mean boxcar filter, leaving behind the slowly varying background. Subtracting this signal from the original flat-field image leaves an image containing the pixel-to-pixel sensitivity changes and objects such as stars and cosmic rays. A bad-pixel mask was used to identify and correct the defects with interpolation from nearby pixels.

The residual images from subtracting the smoothed flat-field images were averaged using a $\sigma$-clipping algorithm to reject pixels affected by stars or cosmic rays. This flat-field–corrected pixel-to-pixel sensitivity differences but failed to remove the overall gradient. This instrumental signature was removed by using the science images themselves. It was assumed that the individual CCD fields on the mosaic, which were farthest from the center of the galaxy and hence least contaminated by stars, should be completely flat. The assumption of intrinsic flatness is justified, as according to the NASA Extragalactic Database (NED), M33 reaches 25 mag arcsec$^{-2}$ in the $B$ filter at a major axis radius of 70.8. The ratio of the major axis to the minor axis
is 1.70. The average $B-V$ index of M33 reported by NED is 0.55, and the sky at Mauna Kea is approximately $V = 21.7$ mag arcsec$^{-2}$ (Krisiunas 1990). Individual CCD images that are outside an ellipse centered on M33 with a major axis radius of 70$'$ and the same ellipticity as M33 were averaged to create a superflat, which was then normalized to unity. Stars were removed from the individual images using PSF fits and also applying the same $\sigma$-clipping algorithm used for the creation of regular flat fields. A minimum of three images per CCD were combined to create the super flat field. Since this calibration is being used for the removal of a slowly changing gradient, the image was smoothed using a $3 \times 3$ mean boxcar. Subtraction of the smoothed image from the original showed a flat image consistent with the expected noise level. The flat-fielded science images were then divided by the super flat field to remove the instrumental gradient.

### 3.3. Photometry

All stellar photometry was performed using the DAOPHOT/ALLSTAR package (Stetson 1987, 1994). As DAOPHOT is unable to handle multextension FITS images, each mosaic frame was split into its individual frames. This gave a total of 612 images, which were all treated independently for the extraction of photometric data.

To account for geometric distortions in the PSFs, 150 stars were selected on each image and used to construct a quadratically varying PSF. The photometric measurements were made with ALLSTAR, which simultaneously fits groups of stars found close to each other on the frame with the PSF. Using photometry from each CCD chip, registration of the chips relative to one another was done with DAOMatch/DAOMaster. This worked well with each individual chip, and a 20-parameter transformation was used to model the geometric distortions, so that the measured pixel positions of the stars on each CCD chip could be matched to other observations of the same field on the same chip. For example, for CCD01 in field 2, there were three sets of observations in each of the four filters. These 12 images were then registered to match common objects for each field. All observations were slightly offset from one another, with the result that some stars were observed on two adjacent detectors. Using these common observations, the complete photometric catalog was pieced together, placing all objects on a common coordinate system, as described in the next section. Our photometry catalog is presented in Table 4.

### 3.4. Astrometric Registration

To identify common objects between adjacent CCDs the pixel coordinate system had to be transferred to J2000 coordinates.

The rationale for this procedure is that DAOMatch/DAOMaster failed to converge to a proper registration solution, as less than 5% of the area of two chips overlapped from the dithered observations. When DAOMaster finds a transformation, it is only valid for the objects in common between the images. Extrapolation of the solution to adjacent CCDs would introduce large distortions. Instead, the pixel coordinate system for each CCD chip was first mapped to the J2000 coordinate system.

Common stars between this survey and the USNO-A2 astrometric catalog were identified by using the mszero and cfind IRAF commands found in the mscred and imcco packages. The cmap program was used to automatically cross-identify 100 common stars in each CCD frame by finding the brightest star within a $20 \times 20$ pixel search box. The success rate was approximately 75%, with a majority of failures due to catalog stars located outside the imaged area. The CCMAP program was then used to compute a rough astrometric solution based on all cross-identifications, including incorrect ones, since the number of true matches dominates the list. These solutions had an rms error of approximately 6". With this plate solution, the Starlink package GAIA was used to identify common stars between the two catalogs. The output from GAIA was input into ccmmap to compute an accurate plate solution. The average rms error was reduced to 0.5", or approximately 2 pixels, which is about the internal accuracy of the USNO-A2 catalog. The entire photometric catalog was then transformed onto the J2000 coordinate system.

This new catalog was searched for duplicate objects that were imaged on adjacent CCDs. These objects were located by identifying the closest neighbor to each object and the closest objects to that neighbor star. If two stars were found to be closer than 1" and their instrumental magnitudes differed by less than 0.1 mag, then those stars were assumed to be the same and combined into a single entry.

### 3.5. Photometric Calibration

The master astrometric catalog was corrected for zero-point instrumental magnitude offsets between each observation, chip, and field. These values were calculated from the identification of common objects in the master catalog. Figure 2 shows the calibration data for stars common to field 1 and 2 for each filter. The lack of scatter, other than the expected photometric errors, confirms that the cross-identification of common objects works very well. The average error for all measured magnitude offsets is approximately 0.01 mag, and the standard deviation from the fit for stars with an instrumental magnitude greater than 14 is approximately 0.02 mag. This is also a measure of the quality of the flat fielding using stars common to field 1 and 2. If any

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**Table 4**

| Star ID | R.A. | Decl. | $V$ | $\sigma_V$ | $V$ | $\sigma_V$ | CN | $\sigma_{CN}$ | TiO | $\sigma_{TO}$ | Sharp |
|--------|------|-------|-----|-----------|-----|------------|-----|-------------|-----|-------------|------|
| 1      | 131 04.68 | 30 52 07.70 | 15.8437 | 0.0423 | 15.1750 | 0.0118 | 9.4495 | 0.0079 | 9.5432 | 0.0088 | 2.8480 | 0.0670 |
| 2      | 130 45.71 | 30 45 01.00 | 16.7190 | 0.0231 | 99.9990 | 0.0366 | 10.3599 | 0.0140 | 4.7347 | 0.1315 |
| 3      | 130 45.15 | 30 51 37.80 | 16.5790 | 0.0048 | 16.0423 | 0.0095 | 10.0849 | 0.0366 | 1.4807 | 0.1440 |
| 4      | 131 03.82 | 30 51 36.90 | 17.4459 | 0.0576 | 99.9990 | 0.0048 | 10.3792 | 0.0116 | 14.6062 | 0.1325 |
| 5      | 131 07.73 | 30 49 09.80 | 17.1538 | 0.1146 | 16.0570 | 0.0768 | 10.2046 | 0.0882 | 18.9920 | 2.0965 |

**Notes:** Table 4 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. Col. (1): star ID; cols. (2) and (3): R.A. and decl. in J2000 coordinates; cols. (4), (6), (8), and (10): $V$, $I$, CN, and TiO magnitudes; and cols. (5), (7), (9), and (11): associated photometric error returned by ALLSTAR. Cols. (12) and (13): $\chi^2$ and Sharp values for the PSF fit from DAOPHOT.
gradients exist, then one would observe a systematic offset in Figure 2 from flat-fielding errors. One potential problem is that the calibration of each chip is dependent only on adjacent chips, and thus the offset will inherit errors from every other chip other than the CCD selected as the zero-point reference. A CCD chip that is five CCDs away from the reference chip could suffer from a large (0.1 mag) systematic offset. This effect was monitored by plotting the color-magnitude diagram (CMD) for the reference chip with that for the CCD chip being corrected superposed. Examination of the CMDs on opposite sides of the mosaic shows no difference greater than 0.05 mag, the accuracy at which any offsets could be detected through the examination of CMDs.

With all of the photometry set to a common instrumental photometric system, transformation to the standard system for the \( V \) and \( I \) filters was computed using data from the DIRECT project (Macri et al. 2001). Comparison of the two photometry data sets is shown in Figure 3. The scatter in this fit for stars brighter than \( V, I = 12 \) is 0.03 and 0.08 mag, respectively. This is consistent with the internal magnitude calibration of the DIRECT project, as seen in Figure 9 of Macri et al. (2001). With errors this large, a reliable color term could not be determined. Instead, only bright stars with a \( V - I \) color less than 0.3 mag were used to determine the zero-point offsets; otherwise the average color terms for CFH12k from the online

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**Fig. 2.**—Photometric offsets between the instrumental magnitudes of field 1 and 2 for each filter. Each field is identified with a subscript.

**Fig. 3.**—Comparison of CFHT instrumental photometry with the DIRECT project for the \( V \) and \( I \) filters. Uppercase letters refer to standards taken from the DIRECT project, and lowercase letters refer to the instrumental photometry from this study. Also shown is the zero-point offset adopted for each filter.
observer’s manual were used. The adopted transformation equations are

\[
\begin{align*}
V &= V_i + 7.39 + 0.001(V_i - I_i), \\
I &= I_i + 6.42 - 0.010(V_i - I_i),
\end{align*}
\]

where \( V_i \) and \( I_i \) are the observed instrumental magnitudes.

Calibration of the TiO and CN magnitudes was much easier. It is expected that the CN – TiO measurements for stars not on the AGB such as the main sequence (MS) should have CN – TiO ≈ 0. These stars lack the strong TiO and CN absorption bands found in the cooler AGB stars, and the TiO and CN filters lie on no strong absorption features. The TiO magnitudes were adjusted such that CN – TiO has an average of zero for stars with \( V – I \) less than 0.8. The true magnitude of a star observed in these filters is irrelevant, as only the difference between them provides a measurement for identification of C and M stars.

3.6. Completeness Tests

Many aspects of this work involve relative counts of star types. When observing a large extended object such as a galaxy, the detected number of stars will vary from region to region because of properties of the galaxy and constraints due to instrumentation. To compare relative statistics across the galaxy the completeness needs to be known as a function of position.

Estimating detection limits due to the galaxy’s structure requires knowledge of the poorly understood dust extinction. Looking at Figure 1, or any \( B \)– or \( V \)-band image of M33, it is easy to identify extinction in spiral arms that is caused by dust. Star counts in dusty regions will be lower, as more stars will fall below the detection limits.

Detection limits due to instrumental constraints are primarily the result of a lack of resolution. Detecting a star requires the isolation of its PSF on an image. In very crowded fields it becomes impossible to separate each stellar component. It is possible to test the confusion limit through Monte Carlo methods.

The Monte Carlo tests, now known as ADDSTAR tests, artificially add stars to a frame and attempt to recover them under the same conditions as the original photometry was obtained. Comparing the input star list to the recovered objects gives a measurement of detection limits and completeness due to instrumental effects. No information is gained about extinction due to dust. ADDSTAR tests were performed using the DAOPHOT and ALLSTAR packages, making use of the ADDSTAR routine. This routine uses the model PSF that was generated from the original photometry extraction to add artificial stars to the image. The star must be added with the same noise characteristics as a star of the same instrumental magnitude. If ADDSTAR tests are to be a valid estimation of the true completeness, then the test must not significantly alter the crowding statistics in the image when adding stars to it. The input stars must also have color indexes similar to the original stars in the image. Thus, the original photometry list is used to generate the artificial input stars.

We added 1000 stars per frame. This number appeared not to make even the most sparse fields (which contain just over 1000 stars) over dense. Analysis of the sparse fields showed that 99.8% of stars added at 100 \( \sigma \) level were recovered, adding confidence that our choice of adding 1000 stars per frame would not affect crowding statistics.

To generate the magnitude of an artificial star and its relative color indexes, binned CMDs and color-color diagrams are used to determine the probability of generating stellar parameters. First, a CN – TiO versus \( V – I \) diagram is binned by 0.1 mag. The number of stars in each bin is divided by the sum of all the bins to generate a probability. A random number between 0.000 and 1.000 is generated, and bins are summed by row \( (V – I) \) then incremented in column (CN – TiO) until the sum of the bin is greater than the random number. This bin determines the CN – TiO and \( V – I \) indexes of the artificial star. Next, a CN versus CN – TiO–normalized grid is used to determine the CN magnitude based on the corresponding CN – TiO column and likewise a \( V \) versus \( V – I \) grid was used to determine the corresponding \( V \) magnitude. The artificial CMDs generated in this manner appeared identical to the original data set. The artificial magnitudes were then transformed back to the instrumental magnitude system using the calibrations from 3.5. The generated number of C stars was close to 100, as there is approximately one C star for every 100 other types of star. Since C star
completeness tests are important in our analysis, the artificially generated star list was changed by taking the logarithmic value of each bin in the weighting grids before normalization. This places more weight on generating stars with small populations. Close to a hundred carbon stars were generated with this alteration, giving good statistics for completeness determinations.

There were 51 exposures between all four filters, and there are 12 chips per exposure. The ADDSTAR test was run 10 times to obtain good statistics for the completeness of the entire stellar population. In total, $6.12 \times 10^6$ stars were added to the frames. Before stars were added to a frame, each CCD for the same field of view was registered using MONTAGE2 from the DAOPHOT package to match star coordinates, using the plate solutions from §3.4 to aid in cross-identification afterward. Geometrically altering an image can introduce noise and artificial artifacts, but this is minimized if the image is over-sampled. The FWHM of a star should be greater than 2 pixels to avoid registration artifacts. Under the best seeing conditions the FWHM was just under 3 pixels in our images. For each image the photometry steps from §3.3 were repeated.

The new photometry lists containing the artificial stars were matched to the artificial-star catalog, and completeness statistics were gathered. In Figure 4 the global completeness level is plotted as a function of position. The spatial scale is identical to Figure 1. One can see that each of the four pointings has a different completeness level, which is due to changing seeing conditions, and that field 3 had more observations that any other field and hence detected fainter stars.

4. RESULTS

4.1. Star Counts

In Figure 5, the spatial distribution of stars appears relatively uniform. This is different from what is observed in star-count distributions for M31, as presented in Figures 2 and 3 of Ferguson et al. (2002). M31, like the Milky Way, has dwarf spherical companions, and their presence can be detected by streams of stars sharing common orbits. In the Milky Way there is the Sagittarius dwarf galaxy, which is currently being sheared apart through gravitational interaction with our Galaxy. Mapping the spatial distribution of evolved stars, such as C stars or RR Lyrae–type variables (Vivas & Zinn 2003), reveals tidal tails from the Sagittarius dwarf. Streams of stars have also been observed emanating from globular clusters such as Pal 5 (Odenkirchen et al. 2001). Thus, if M33 has unseen companions, their presence could be betrayed in a complete star map by selecting specific stellar populations.

Visual examination of the raw star map for M33 does not reveal any obvious perturbations. However, if accreted satellites have no luminous stellar component (White & Rees 1978; Dekel & Silk 1986), their presence could be hidden in stellar density maps. A more detailed exercise is to examine distributions of specific stellar populations that represent different epochs of star formation, tracing the dynamical history of the galaxy through perturbations of its stellar population. To do
this, we need to examine the CMDs of M33 and identify relevant populations.

### 4.2. Color-Magnitude Diagrams

In Figure 6, a calibrated CMD for $I$ versus $V - I$ is presented for stellar objects from our survey with errors in the color term less than 0.05 mag. The MS, supergiant branch (SGB), RGB, and AGB are all visible. In Figure 6 the MS is seen as a strong vertical band in the range $-0.5 \leq V - I \leq 0.35$. This represents young, luminous blue stars and provides a tracer of very recent star formation. Using Padua theoretical isochrones (Girardi et al. 2000) for a young stellar population (age $6.31 \times 10^7$ yr) and adopting a distance modulus of 24.64 (Freedman et al. 1991) gives a mass of approximately $5.8 M_\odot$ at $V = 22$ for a stellar population with $Z = 0.008$. The large number of MS stars is no surprise, as the spiral arms in M33 are regions of active star formation.

The red SGB is seen as a band of stars extending to $V \approx 19$, $V - I \approx 2$ out from the RGB, which is seen as a large clump centered at $V \approx 22.5$, $V - I \approx 1.5$. The AGB population, where C stars will be found, is the band of stars with $V - I \gtrsim 2$ and $V \lesssim 21$. Foreground contamination from Galactic stars is seen as a vertical sequence at $V - I \approx 0.8$ extending up to $V = 15$, the saturation limit of the detector. This CMD is a very useful tool for isolating specific stellar populations, as is seen in §§ 4.3 and 4.5.

The distribution of stars on the CMDs is a result of star formation, stellar evolution, and extinction. The effects of star formation and stellar evolution are observed through the presence of very young OB stars and older RGB and AGB stars. Extinction has the effect of blurring the CMD by shifting observations dimmer and redward. Since the amount of extinction depends upon the line of sight, stars with the same intrinsic luminosity and color can appear at different locations in the CMD.

### 4.3. CMD-Selected Star Counts

The substructure of halos and disks of nearby galaxies contains clues about hierarchical galaxy formation. State-of-the-art simulations (Klypin et al. 1999; Moore et al. 1999) show that accreted subhalos last much longer than previously thought, with the central core lasting several tidal timescales (Hayashi &...
Navarro 2002), and several hundred cores could reside in galaxies like the Milky Way and M33.

Our survey data allow us to select specific stellar populations over most of M33’s disk. The observed MS reflects recent star formation, since the MS lifetimes for the massive and luminous stars are short (less than 1 Gyr). MS stars were chosen as stars with \( V - I \) colors less than 0.35 mag. The resulting distribution is shown in Figure 7. As should be expected, the spiral arm patterns seen in Figure 1 are also well traced by luminous MS stars. The bottom panel of Figure 7 is a binned map of MS stars with \( 15 < V < 22 \) that has been completeness-corrected using the data from § 3.6. This map shows all MS stars with masses greater than \( 6 M_\odot \) and the major spiral arms of the galaxy are well traced. The center of M33 appears as a hole, as stellar crowding is too great to allow reliable detection of any stars in the region. The application of stellarity cuts eliminated all detections in this region of the galaxy.

The same exercise can be applied to the SGB population. SGB stars are identified by selecting all stars with a \( V - I \) color greater than 1.2 and a \( V \) magnitude less than 21.75. Faint stars are excluded to avoid RGB stars at the base of the RGB clump. The distributions of SGB stars are shown in Figure 8. Like the MS stars, the SGB population is relatively young and traces out stellar populations with ages less than about 1 Gyr. The SGB map suffers from foreground contamination by M-dwarfs, seen as a scatter of stars over all observed fields, but the galaxy is still identifiable. The SGB population is largest in areas containing the most MS stars. This occurs because both groups of stars have similar ages and the MS lifetimes are longer than stars found in the SGB phase. Both the SGB and MS maps (Figs. 7 and 8) trace out a high-density structure that almost encloses the center of the galaxy. This feature starts on the east side of the galaxy, where it then sharply turns eastward toward the galaxy center and then blends into two spiral arms that extend northward.

The spatial distribution of AGB stars is shown in Figure 9. The population shows a smooth distribution of stars compared with the clumpy distribution of MS stars. This is due to dispersion of the AGB population. M33 itself shows many localized regions of massive star birth, such as the gas complex NGC 604. Over time, new stellar associations disperse. Thus, the distribution of MS stars appears clumpier than that of AGB stars.

The AGB star map does not show any extended structure apart from gently tracing out the spiral arms. At semimajor radii...
larger than 30', the AGB population of M33 is lost because of foreground confusion from Galactic red dwarfs. Just as with MS stars, incompleteness is strongest toward the center of M33, creating an apparent hole.

4.4. Color-Color Diagrams

The broadband photometry can be combined with the narrowband photometry to discriminate between spectral subtypes, namely, C stars and M stars. Figure 10 shows the color-color diagram for the entire M33 field. The carbon stars, which have strong CN absorption bands, appear as an isolated group with an average CN – TiO index of 0.5. The M stars, with strong TiO absorption bands, tail off from the RGB population at approximately $V - I = 2$ toward redder colors or later spectral types. There is a difference of about 1 mag between the CN – TiO index values of C stars and M stars; the CN and TiO filters clearly do a good job at selecting AGB subtypes.

M31 has a distance modulus of 24.47 (Durrell et al. 2001), and M33 has a measured distance modulus of 24.64 (Freedman et al. 1991). The 1 σ errors in the measurements are approximately ±0.15 and thus to within 1 σ, M31 and M33 are at the same distance. To define the selection boxes for choosing M stars and C stars, the criteria of Brewer et al. (1996) for M31 are adopted. C stars are identified with CN – TiO > 0.3 and M stars with CN – TiO < –0.2, and both types must have $V - I > 1.8$. These were originally chosen by spectrally identifying C and M stars and selecting color values that encompassed C stars without contamination (see Brewer et al. 1996 for details).

Figure 11 shows a CMD for the 7936 C stars selected using the adopted criteria. The completeness limit is discussed later in this section. As expected, these stars occupy the AGB branch location of the CMD. The foreground contamination of C stars from the Milky Way is unimportant, the surface density being only 0.019 deg$^{-2}$ (Green 1992) down to $V = 18$.

The M star population suffers strong contamination from the Milky Way. NGC 6822 (at $b = -18^\circ$) was observed to have approximately 9000 foreground stars over a $28' \times 42'$ field of view (Letarte et al. 2002). M33 ($b = -31^\circ$), while at a higher Galactic latitude, still suffers substantial M star foreground contamination (see § 4.5). Contamination from non-AGB members within M33 is not a serious problem, as members of the RGB and SGB populations do not have strong CN or TiO absorption bands. However, choosing an $I$-band magnitude cut
limits foreground contamination and contamination from non-AGB stars in M33. Using Figure 11, C stars and M stars also have $I$ magnitudes between 18.5 and 21. These values were chosen to enclose a majority of the detected C stars without straying far below the 100% completeness limit. To quickly estimate the completeness limit in the $I$ band, the raw luminosity function (LF), shown in Figure 12, was used. The number of stars rises approximately linearly toward fainter magnitudes, until approximately $I = 22$ mag, when the number of objects quickly declines as the detection limit is reached.

4.5. Color-Color Diagram—Selected Star Counts

As a continuation of § 4.3 we can now examine the AGB stellar content of M33. Figure 11, C stars and M stars also have $I$ magnitudes between 18.5 and 21. These values were chosen to enclose a majority of the detected C stars without straying far below the 100% completeness limit. To quickly estimate the completeness limit in the $I$ band, the raw luminosity function (LF), shown in Figure 12, was used. The number of stars rises approximately linearly toward fainter magnitudes, until approximately $I = 22$ mag, when the number of objects quickly declines as the detection limit is reached.

4.5.1. Tidal Interactions

There is no evidence of tidal disruption within the C star population, and nor is there indication of C stars originating from a different system. This is in contrast to the claim of Block et al. (2004), who state that M33 displays “spectacular
arcs of carbon stars” beyond 14’ from its nucleus. The lack of external interactions may be a reason why M33 displays beautiful grand-design spiral arms that can be traced from the outermost regions of the disk directly toward the center of the galaxy. The bottom panel in Figure 14 shows the corresponding M star distribution. It is similar to the C star distribution, except that foreground contamination, from Milky Way M dwarfs, is stronger.

4.5.2. Radial Distributions

The radial distribution of stars in a galaxy allows a quantitative measurement of the galaxy’s morphology. To extract radial profiles from M33, its tilt must be taken into account. To do this, shape parameters for M33 from the Third Reference Catalogue of Bright Galaxies (RC3) were obtained from NED, specifically the length of the semimajor axis and the ratio of the semimajor axis to the semiminor axis. If M33 were seen face-on, its shape would be a circle. Ellipses centered on M33 were constructed with different radii, and star counts were made for each radius using completeness-corrected C and M star counts. Figures 15 and 16 show the deprojected radial profile for M33 for C stars and M stars, respectively, in units of ln (number of stars arcsec$^{-2}$).

Examining the C star profile, we see that it is flat from the center of M33 out to 15’, and then the number density of stars decreases out to 50’. Here the slope changes again and becomes flat out to approximately 70’, beyond which there are too few C stars to provide useful statistics. The M star profile is qualitatively similar to the C star profile. The number density of M stars decreases out to about 20’ from the center of the galaxy, where there is a steepening of the slope and the distribution drops off. This feature can be seen in the bottom panel of Figure 14 as a separation between the inner and outer disk in the distribution. At 45’, the foreground population of M stars becomes dominant, reducing the slope of the M star population out to the edge of the field of view.

4.5.3. Metallicity Gradients

The time needed for a stellar population to produce the majority of its carbon stars is about 1 Gyr; thus, for stellar populations older than this the C/M ratio is independent of the star formation history (Mouhcine & Lanc$\mathrm{on}$ 2003). Since the ratio
of C to M stars is a tracer of metallicity, the C and M star profiles can be converted into a completeness-corrected C/M ratio profile. Before this can be done, the foreground population of M stars needs to be estimated. It is assumed that this population of M stars is uniform across the field. The M star profile is then used to estimate the foreground population. This was done by assuming that the M star profile has a constant value beyond 25′ obeying an exponential disk profile. The foreground M star population was in this way estimated to be 0.50 ± 0.03 arcmin⁻². This gives approximately 2300 foreground M stars over the field of view. As a check the foreground population can also be easily calculated by counting stars at the periphery of the image. All M stars with right ascension greater than 1h 36m were considered to be foreground M stars, as this area contains few C stars. The completeness-corrected stellar density of M stars in this region was found to be 0.55 ± 0.03 arcmin⁻², consistent with our derived value. Figure 17 shows the C/M ratio as a function of galactocentric radius. The ratio increases to a radius of 12′ and then flattens for the outer disk regions. This result indicates that the metallicity of M33 is high in the center and low in the outer parts of the disk, with a change in the gradient along the way. This is compatible with other metallicity gradient measurements (Vilchez et al. 1988).

These results are consistent with viscous disk formation models that predict exponential surface luminosity profiles of spiral galaxy disks (Zaritsky 1992). The rotation curves of spiral galaxies show solid-body rotation in the inner parts of the disk and flat rotation curves in the outer part of the disk, where the rotation curve is dominated by dark matter. For solid-body rotation there is no angular velocity difference between material at different radii, which means that there is no viscous drag or turbulent diffusion. In the outer parts of the disk, the opposite is true with the production of radial gas flows. In galaxy formation models, negative abundance gradients are produced (Sommer-Larsen & Yoshii 1990), and the evolutionary effect of rotation then smooths the metallicity gradient in the outer disk where the rotation curve is flat. Radial outflows transfer metal-rich material into metal-poor material and vice versa with radial inflows. This produces a metallicity distribution with a change in slope where the rotation curve flattens. Examination of the 21 cm rotation curve for M33 (Corbelli & Salucci 2000) reveals that, in fact, the rotation curve flattens around 10′−15′, consistent with our findings.

The current data set allows for a C/M ratio map for M33. This completeness-corrected map is shown in Figure 18. The increase in the C/M ratio with increasing radius is apparent, as
are two regions with a high C/M ratio. The areas of enhanced C/M ratio are located in the regions where the arcs mentioned in Block et al. (2004) are to be found. The number of M stars and C stars drops toward the edge of the disk, and thus the error in the C/M star measurement will be higher in these regions. The second and third panels in Figure 18 show the associated error and the signal-to-noise ratio (S/N) for each region in the C/M ratio map. The peak in the northern region of high C/M has a S/N less than 3, and its associated error in the ratio is approximately 0.35, making the detection of the peak with the bin size used somewhat uncertain. The same argument applies to the southwest region of the map.

To test whether the enhanced C/M ratio regions are statistically significant, the S/N can be increased by increasing the bin size to avoid small-number statistics. The C/M ratio map was rebinned with an area 4 times greater. The north and southwest regions each have average C/M ratios of 0.5 and 0.6 ± 0.04, respectively. Other regions around the edge of the disk show C/M ratios no higher than 0.4. It thus appears that the higher C/M ratios are real. These regions could simply mark the outer reaches of spiral arms with lower metallicities. Both regions do have spiral arm structure within them. Figure 19 shows a CMD for a region located at the edge of the visible disk of M33. The stellar populations and features of the CMD in Figure 6 are still visible. However, the CMD does not show any significant morphological differences. A deeper survey is necessary to search for a distinctive stellar population in the region, which could consist of an old, low-luminosity stellar population.

The first panel in Figure 18 also shows that the C/M ratio is a function of galactocentric radius. This gives the galaxy the appearance of being surrounded by a ring of material with a lower metallicity. It has recently been suggested that the Milky Way is also surrounded by a ring traced by stars of lower metallicity (Ibata et al. 2003). As suggested by Ibata et al. (2003), this feature could be extended spiral arm structure. In galaxy formation simulations the edge of the disk is expected to be young and to contain metal-poor gas (Navarro & Steinmetz 1997). In M33, the regions of low metallicity also correspond to the edge of the disk, as traced by C and MS star populations. In the Milky Way distinct spiral arm structure has been identified from 21 cm emission (Davies 1972; Ibata et al. 2003). This similarity suggests that the Milky Way “ring” may be consistent with spiral arms and does not require tidal interaction of dwarf galaxies for its formation. We may be seeing the same effect here in M33.

4.6. C Star Luminosity Function

This study has identified 7936 C stars, and Figure 20 shows the corresponding completeness-corrected LFs for V, I, and bolometric magnitudes. The LF is similar to those observed in other systems, such as M31 and the SMC, as shown in Groenewegen (2002). To calculate absolute bolometric magnitudes for the C stars we used a distance modulus of 24.64 (Freedman et al. 1991) with the bolometric correction (BC) given by Bessell & Wood (1984) for M stars.

\[
M_{\text{bol}} = I + BC - 24.64, \\
BC = 0.3 + 0.38(V - I) - 0.14(V - I)^2.
\]
The C star luminosity function (CSLF) has a narrow peak and thus has potential as a good distance indicator (Richer 1989; Groenewegen 2002). The problem is disentangling the dependence of the peak magnitude of the CSLF on galactic properties such as metallicity or star formation history. Figure 8 of Groenewegen (2002) shows that the mean of the CSLF does not depend on [Fe/H], with most systems having a mean bolometric magnitude between $-4$ and $-5$. Discrepancies can be explained either through incompleteness of the CSLF at faint magnitudes causing the mean to be too bright or the absence of an intermediate-age population, leaving only faint C stars. In M33 the average bolometric magnitude is found to be $-4.2 \pm 0.1$ mag, which is similar to M31 and the SMC (both have $M_{bol} = -4.3$). Because such diverse systems have similar C star LFs, C stars could be used as distance indicators.

5. CONCLUSIONS

Using a four-band photometric system, we have classified the AGB stars in the nearby spiral galaxy M33 into C and M star types. The photometry catalog allowed us to examine the different stellar populations of M33. M33 has a large number of MS OB stars being produced by current star formation. The extent of the disk and spiral arm structure was shown through examination of the spatial distributions of MS and SGB stars. The AGB population, being older, is dispersed and only tenuously trails the spiral arm structure. The distribution of the AGB stars revealed no smaller galactic companions, such as those found in the local environments of M31 or the Milky Way.

Using color-color diagrams, the C and M star populations were used to map the C/M star ratio. The C/M star ratio is known to trace metallicity, and the C/M ratio profile and C/M star map were produced. The C/M star profile shows a metallicity gradient dependent on galactocentric radius. The profile was found to flatten at the same radius at which the radial velocity profile also flattens. These results are consistent with viscous-disk formation models, in which the metallicity gradient becomes flattened in the outer part of the disk as material originating at different initial radii become mixed.

The C/M star map shows the outer parts of M33’s galactic disk to be metal-poor. This can give the appearance to an observer located inside the galaxy that they are surrounded by a ring of metal-poor material. The C/M star map also shows two regions with an enhanced C/M star ratio. These regions may be a natural occurrence at the end of a spiral arm, or they may trace a different underlying population. These regions require deep follow-up photometric surveys to allow examination of the stellar populations in order to explain the implied lower metallicity in these regions.

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