THE DIRECT PROJECT: CATALOGS OF STELLAR OBJECTS IN NEARBY GALAXIES.
I. THE CENTRAL PART OF M33

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ABSTRACT

The DIRECT project aims to determine direct distances to two important galaxies in the cosmological distance ladder—M31 and M33—using detached eclipsing binaries (DEBs) and Cepheids. The search for these variables requires time-series photometry of large areas of the target galaxies and yields magnitudes and positions for tens of thousands of stellar objects, which may be of use to the astronomical community at large. During the first phase of the project, between 1996 September and 1997 October, we were awarded 95 nights on the F. L. Whipple Observatory 1.2 m telescope and 36 nights on the Michigan-Dartmouth-MIT 1.3 m telescope to search for DEBs and Cepheids in the M31 and M33 galaxies. This paper, the first in our series of stellar catalogs, lists the positions, three-color photometry, and variability indices of 57,581 stars with 14.4 < V < 23.6 in the central part of M33. The catalog is available from our FTP site.

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

On-line material: machine-readable tables

1. INTRODUCTION

The DIRECT project (Kaluzny et al. 1998; Stanek et al. 1998) started in 1996 with the long-term goal of obtaining distances to two important galaxies in the cosmological distance ladder—M31 and M33—using detached eclipsing binaries (DEBs) and Cepheids. These two nearby galaxies are the stepping stones in most of the current effort to understand the evolving universe at large scales. Not only are they essential to the calibration of the extragalactic distance scale, but they also constrain population synthesis models for early galaxy formation and evolution. However, accurate distances are essential to make these calibrations free from large systematic uncertainties.

The search for detached eclipsing binaries and Cepheids in our target fields requires the detection of a large number of stellar objects in our CCD frames and the repeated measurement of their fluxes over a relatively large time baseline, usually of the order of 1–2 yr. Since the goal of the project is not simply the detection of these variables but the determination of accurate distances to the target galaxies, we must also undertake a rigorous absolute calibration of our photometry. The resulting catalogs of objects contain tens of thousands of objects, out of which we only select a few hundred for distance-scale work. However, the astronomical community at large may benefit from the existence of an accurate, well-calibrated list of objects in these nearby, well-studied galaxies. This is our rationale for the publication of these series of catalog papers.

Messier 33 (NGC 598) is one of the main components of the Local Group of galaxies. It is classified as a SA(s)cd galaxy in the Third Reference Catalog of Galaxies (de Vaucouleurs et al. 1991) and as a Sc(s)II-III in the Revised Shapley-Ames Catalog (Sandage & Tammann 1981). It is located at a right ascension of 1°34′ (J2000.0), and it has major and minor B25 isophotal diameters of 71′ and 42′, respectively. It has been extensively studied, appearing in more than 1000 publications. One of first was that of Hubble (1926), who stated in the abstract of his paper that its “great angular diameter and high degree of resolution, suggesting that it is one of the nearest objects of its kind, offer exceptional opportunities for detailed investigation.”

The present work will describe the details of the observations (§ 2), the reduction and absolute calibration of the data (§ 3), the creation of the stellar catalog (§ 4) and the results of our consistency checks (§ 5) for three CCD fields in the central part of M33. The analysis of the variable stars located in these fields will be analyzed in two upcoming papers by Macri et al. (2000) and Stanek et al. (2001).

2. OBSERVATIONS

Our observations of the central region of M33 were primarily carried out at the Fred L. Whipple Observatory (hereafter FLWO) 1.2 m telescope. We used “AndyCam” (Szentgyorgyi et al. 2000), a thinned, back-illuminated, AR-coated Loral 2048 pixel CCD camera with a plate scale of 0.317 pixel−1, or an effective field of view of 10′.8. The filters used during our program were standard Johnson B and V and Cousins I. Additional I-band data were collected at the Michigan-Dartmouth-MIT Observatory 1.3 m McGraw-Hill telescope. We used “Wilbur” (Metzger, Tonry, & Luppino 1993), a thick, front-illuminated Loral 2048 pixel CCD camera. The plate scale and field of view were almost identical to that of AndyCam.

We observed three fields located north, south, and southwest of the center of M33, which we labeled M33A, B,
and C. The J2000.0 center coordinates of the fields are: M33A, right ascension = 01°34'05.1", declination = 30°43'43"; M33B, right ascension = 01°33'55.9", declination = 30°34'04"; M33C, right ascension = 01°33'16.0", declination = 30°35'15". Figure 1 shows the boundaries of these fields overlaid on a digitized image of the galaxy from the POSS-I survey,4 while Figure 2 shows a mosaic of the survey fields, created with our CCD data. At FLWO, we obtained V and I data on 42 nights and B data on 13 nights. At MDM, we obtained I data on 10 nights. Exposure times were 1200 s in B, 900 s in V, and 600 s in I. Fields were observed repeatedly on each night in V and I, so the actual number of exposures per field in those filters is around 110 and 60, respectively. Standard star fields from Landolt

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4 The Digitized Sky Surveys were produced at the Space Telescope Science Institute under grant NAG W-2166. The National Geographic Society-Palomar Observatory Sky Atlas (POSS-I) was made by the California Institute of Technology with grants from the National Geographic Society.

**Table 1**

| UT Date | MJD  | Field | Band | Tel. | Seeing |
|---------|------|-------|------|------|--------|
| 1996 Sep 3 | 329.7615 | M33A | I | F | 1.40 |
|         | 329.7786 | M33A | I | F | 1.24 |

Note.—Table 1 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.

* Photometric night—standards observed. Telescope code: F = FLWO; M = MDM.
(1992) were observed on one photometric night. Table 1 presents a log of our observations.

3. DATA REDUCTION AND CALIBRATION

3.1. PSF Photometry

Paper I of the DIRECT variable star series (Kaluzny et al. 1998) contains a detailed description of the data reduction and PSF photometry. Only a brief summary of these procedures is presented here. The CCD frames were processed using standard CCDPROC routines under IRAF. Point-spread functions (PSFs) were calculated from bright and isolated stars present in each frame, following an iterative process. Figure 3 shows a histogram of the seeing for the three filters; median FWHM values were 1.5 for $I$ and 1.8 for $B$ and $V$. After running DAOPHOT and ALLSTAR on all frames, we selected an image of particularly good quality (in terms of seeing and depth) as a “template” frame. ALLSTAR was run again in “fixed-position” mode on all other images, using the transformed object list from the template frame as input. The resulting photometry lists were transformed back into the coordinate and instrumental magnitude system of the template image. The latter was accomplished by computing a local magnitude offset for each star, using high SNR stars ($\sigma < 0.03$ mag) located within a radius of 350 pixels. In cases where few stars met these conditions, the search radius was increased to 750 pixels, or a global median offset was used as a last resort. The magnitude offset between each frame and the template image was recorded in a log file for future

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$^5$ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Associations of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
The instrumental PSF magnitudes present in the databases had to be transformed into the standard system. This procedure can be separated into three steps: (1) transform PSF magnitudes in the instrumental system of the template frame to PSF magnitudes in the instrumental system of the photometric frame; (2) transform PSF magnitudes in the instrumental system of the photometric frame to aperture magnitudes in the instrumental system of the photometric frame; (3) transform the instrumental system of the photometric frame to the standard system. These steps are described in detail below.

3.2. Aperture Corrections

The first step of the photometric calibration process was the transformation of the PSF magnitudes of the photometry database from the magnitude scale of the template frame to the magnitude scale of another frame, taken under photometric conditions (hereafter referred to as the photometric frame). This was easily achieved by applying a magnitude offset of equal size and opposite sign to the one which had already been determined (as part of our automated pipeline) to exist between the template frame and the photometric frame.

The second step of the process was the transformation of PSF magnitudes into aperture magnitudes, through the determination of aperture correction coefficients. Given the crowded nature of our fields, their rapidly varying sky backgrounds, and the relatively poor seeing of our photometric night, a thorough approach was required. We chose one frame for each field and filter combination, and used the master star lists and the PSFs derived by our automated pipeline to remove all objects present in these images, with the exception of bright, isolated stars. Aperture photometry was carried out on these star-subtracted frames at a variety of radii (ranging from 10 to 20 pixels, or 3′ to 6′). The local sky was characterized using an annulus extending from 30 to 40 pixels.

The aperture photometry measurements of all bright stars in a particular frame were examined simultaneously by visually inspecting their curves of growth (i.e., plots of aperture magnitude vs. radius). Objects with unusual growth curves were discarded. The aperture photometry measurements of the remaining bright stars (hereafter, input stars) were analyzed using DAOGROW (Stetson 1990). This program performs an analytical fit to the growth curves of all input stars in all frames, and the resulting function is used to determine a mean growth curve for each frame. DAOGROW then uses the best combination of aperture photometry and growth curve for each input star to calculate its aperture magnitude at the outermost radius (in our case, 20 pixels). Lastly, the PSF and aperture magnitudes of all input stars in each frame are used to derive a mean value of the aperture correction, which is applied to all objects. The aperture correction coefficients derived using this procedure ranged from −0.10 to +0.24 mag, with typical uncertainties of 0.03 mag.

3.3. Photometric Solutions

Once the instrumental PSF magnitudes in each of the nine databases were converted to instrumental aperture magnitudes, the last step required to transform them into standard magnitudes was the derivation of photometric zero points. On 1997 October 9, a photometric night of average seeing quality for our program (I: 1′8; B and V: 0.2′;
we observed six fields from Landolt (1992), containing a total of forty-three standard stars, at air masses ranging from 1.12 to 2.12. We performed photometry on the standard stars using DAOPHOT with the same settings used for the program stars, namely an aperture radius of 20 pixels and a sky annulus extending from 30 to 40 pixels. We used the IRAF PHOTCAL routines to solve for a photometric solution of the form

\[ M_{\text{std},i} = m_{\text{obs},i} + \chi_i - k_i X + \xi_{ij}(M_{\text{std},i} - M_{\text{std},j}), \]  

(1)

where \( M_{\text{std},i} \) and \( M_{\text{std},j} \) are the magnitudes of a star in the standard system in the \( i \) and \( J \) filters, while \( m_{\text{obs},i} \) is the

| Filter | \( \chi \) | \( k' \) | \( \xi \) | rms |
|--------|--------|--------|--------|-----|
| \( B \) | \( (B - V) \) | \(-22.953\) | 0.212 | -0.033 | 0.030 |
| \( V \) | \( (B - V) \) | \(-22.720\) | 0.127 | 0.032 | 0.016 |
| \( V \) | \( (V - I) \) | \(-22.714\) | 0.123 | 0.035 | 0.016 |
| \( I \) | \( (V - I) \) | \(-22.719\) | 0.064 | -0.051 | 0.021 |

**TABLE 3**

| ID | R.A. | Decl. | \( V \) | \( I \) | \( B \) | \( \sigma_V \) | \( \sigma_I \) | \( \sigma_B \) | \( J_8 \) |
|----|------|-------|--------|--------|------|-------------|-------------|-------------|------|
| D33J013251.1+303923.7..... | 01 32 51.11 | 30 39 23.65 | 19.97 | 18.14 | \( \ldots \) | 0.03 | 0.03 | \( \ldots \) | 0.12 |
| D33J013251.1+303741.8..... | 01 32 51.13 | 30 37 41.81 | 21.61 | 21.65 | \( \ldots \) | 0.11 | 0.28 | \( \ldots \) | 0.12 |
| D33J013251.1+303954.9..... | 01 32 51.14 | 30 39 54.86 | 21.72 | 19.50 | \( \ldots \) | 0.12 | 0.13 | \( \ldots \) | 0.06 |
| D33J013251.2+303736.4..... | 01 32 51.17 | 30 37 36.44 | 20.20 | 19.61 | \( \ldots \) | 0.04 | 0.08 | \( \ldots \) | 0.09 |
| D33J013251.2+303907.1..... | 01 32 51.20 | 30 39 07.09 | 22.87 | 21.82 | \( \ldots \) | 0.26 | 0.27 | \( \ldots \) | -0.02 |

*Note.—Table 3 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.*

**FIG. 5.—** Color-magnitude diagrams of the stars present in our catalog. The dashed lines indicate the extent of our data, set by our limiting magnitudes of \( B \sim 24 \) and \( I \sim 22 \).
instrumental magnitudes of the same star in the $i$ filter. $\chi_i$ is the magnitude zero point at $X = 0$, $k_i'$ is the air-mass coefficient for the $i$ filter, and $\zeta_{ij}$ is the color term. The $V$-band solution was calculated using both $B-V$ and $V-I$ for the color term; the latter one was used by default in the calibration process, unless only $B$ and $V$ data were available for a particular object. The $B$-band solution was calculated using $B-V$ for the color term, while the $I$-band solution was calculated using $V-I$ for the color term. The values and uncertainties of the coefficients of each term are presented in Table 2; based on those numbers, we estimate a total uncertainty of $0.02$ mag in our solutions.

Based on the uncertainties associated with PSF magnitude offsets ($0.02$ mag, §3.1), aperture correction coefficients ($0.03$ mag, §3.2) and photometric solutions ($0.02$ mag, previous paragraph), we estimate a total random uncertainty in our photometric zero points of $0.04$ mag.

4. THE STAR CATALOG

Once the photometric calibrations were applied, we merged the $BVI$ databases of each field into a single catalogs. Objects were matched from the master $B$, $V$, and $I$ star lists of each field and were kept only if they had been detected in the $V$ band and in either of the $B$ or $I$ bands. Next, we transformed the object coordinates into the FK5 system using stars from the USNO-A2.0 catalog (Monet et al. 1998). We solved for a cubic-order transformation using software developed by Mink (1999). The solutions used 30–70 stars and had rms values of $0^\prime.4$.

Lastly, the catalogs of the three fields were merged into a single, master catalog. There was—by design—significant overlap between fields A and B as well as between fields C and B; objects in these regions were matched to test the internal consistency of our astrometric and photometric calibrations (see §5). To avoid duplication of these objects, we kept the entry belonging to field B in the final catalog.

As described in Kaluzny et al. (1998), the magnitude uncertainties reported by DAOPHOT/ALLSTAR are underestimated for bright stars and overestimated for faint ones. The errors were rescaled following the precepts established in that paper. Lastly, we calculated mean $BVI$ magnitudes and $V$-band $J_s$ variability indices (Stetson 1996). The catalog is presented in Table 3; it lists IDs, celestial coordi-
Fig. 7.—Comparison of mean magnitudes for bright stars ($B < 19.5$ mag; $V < 19.5$ mag; $I < 19.0$ mag) located in the overlap regions between fields A-B and C-B. The photometric zero points and aperture correction coefficients are determined independently for each field, so these comparisons allow us to check the internal consistency of our reductions. The average values and rms deviations of the offsets are listed in the top left corner of each panel and in Table 4.

5. TEST OF PHOTOMETRIC AND ASTROMETRIC CALIBRATIONS

We performed an internal test of our photometric calibration by comparing the mean $B$, $V$, and $I$ magnitudes of bright stars present in the overlap regions. We imposed magnitude cuts of 19.5, 19.5, and 19.0 mag in $B$, $V$, and $I$, respectively, which restricted the number of matches to about 200, 300, and 400, respectively. On average, the offsets were $<0.01$ mag. This indicates that PSF variations across the field were properly taken into account by DAOPHOT and our pipeline and that the aperture corrections were properly determined. Table 4 lists the values of the offsets and their standard deviations; Figure 7 shows plots of these comparisons.

We performed two external tests of our photometric calibration. In the first test, we matched about 200 objects in common between field C and field 4 of Wilson et al. (1990). The average values and rms deviations of the offsets are listed in the top-left corner of each panel and in Table 4.

We flagged objects as candidate variables if they met two requirements: a $J_s$ index larger than 0.75 and a $V$-band magnitude uncertainty larger than 0.04 mag. The second criterion was introduced to remove bright stars with small variability from our sample of candidate variables (in this data set, it removed 107 stars with $V < 19.5$ mag). Our final sample of candidate variables consists of 1,298 stars. The panels of Figure 6 show some global properties of the variable stars present in our catalog.

### Table 4

| Band | $\Delta$ mag | $m_{lim}$ | $N$ |
|------|--------------|----------|-----|
| **Internal overlap regions:** | | | |
| $V$ | $-0.003 \pm 0.003$ | 19.5 | 327 |
| $I$ | $+0.014 \pm 0.002$ | 19.0 | 357 |
| $B$ | $-0.003 \pm 0.004$ | 19.5 | 160 |
| Wilson et al. (1990): | | | |
| $V$ | $-0.041 \pm 0.058$ | 20.0 | 26 |
| $I$ | $-0.032 \pm 0.068$ | 20.0 | 30 |
| $B$ | $-0.024 \pm 0.108$ | 20.0 | 20 |
| Bersier et al. (2001): | | | |
| $V$ | $-0.031 \pm 0.047$ | 18.5 | 39 |
| $B$ | $-0.038 \pm 0.033$ | 18.5 | 31 |

The catalog can also be retrieved from the DIRECT FTP site at http://cfa-www.harvard.edu/~kstanek/DIRECT.
common between our field C and field 4 of Wilson, Freedman, & Madore (1990). We compared the mean $B$, $V$, and $I$ magnitudes of stars brighter than 20.0 mag in each of the filters (about 25 stars filter$^{-1}$) and found offsets of the order of $\sim 0.03$ mag (brighter DIRECT magnitudes). In the second external test of our photometric calibration, we matched about 4000 objects in common between our field A and one of the fields of Bersier et al. (2001). We compared the mean $B$ and $V$ magnitudes of stars brighter than 18.5 mag (about 35 stars filter$^{-1}$) and again found offsets of the order of $\sim 0.03$ mag (brighter DIRECT magnitudes). Table 4 lists the results of these comparisons, which are also plotted on Figures 8 and 9.

6. ARTIFICIAL STAR TESTS

The differences between our photometry and the Wilson et al. (1990) and Bersier et al. (2001) photometry are small but consistent. Furthermore, both groups used larger telescopes (CFHT and WIYN, respectively) under significantly better seeing conditions than us. Therefore, we decided to undertake artificial star tests to quantify the level of photometric bias that could arise due to the poorer spatial resolution of our images.

We used DAOPHOT to inject 2500 artificial stars into the nine master frames, using the PSFs previously derived by our automated reduction pipeline and taking into account photon noise and other detector characteristics. We analyzed the frames using the same procedures as in the automated pipeline. The results were quite similar for the three frames pertaining to each band, and thus the data files were merged to improve the statistics. Our results are presented in Table 5 and in Figure 10.

Bright stars ($15 < m < 18$) are affected by crowding at the 0.01–0.04 mag level. The bias becomes stronger for fainter objects ($m > 18$), reaching 0.05–0.08 mag. At a given magnitude, the bias increases from $B$ to $V$ to $I$. In all cases, the offset induced by crowding is in the same direction as the offset found between our data and other catalogs.

7. SUMMARY

We have observed three fields in the central part of M33 at the Fred L. Whipple Observatory 1.2 m and the Michigan-Dartmouth-MIT Observatory 1.3 m telescopes. We have performed PSF photometry of objects in these fields, calibrated in the standard system with a zero-point accuracy of $\pm 0.04$ mag.
We have compiled a catalog of positions, \(B\), \(V\), and \(I\) magnitudes, and \(V\)-band variability indices for 57,581 stars with \(14.4 < V < 23.6\). The catalog is available from our FTP site.

The analysis of the variable star content of these fields will be presented in two upcoming papers by Macri et al. (2000) and Stanek et al. (2001).

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