The Panchromatic Hubble Andromeda Treasury: Triangulum Extended Region (PHATTER). I. Ultraviolet to Infrared Photometry of 22 Million Stars in M33

Benjamin F. Williams1, Meredith J. Durbin1, Juliane J. Dalcanton1, Dustin Lang2, Leo Girardi3, Adam Smercina1, Andrew Dolphin4,5, Daniel R. Weisz6, Yumni Choi7, Eric F. Bell8, Erik Rosolowsky9, Lea Hagen7, Karl D. Gordon7, Anil Seth12, Karoline Gilbert7, Puragra Guhathakurta13, Tod Lauer14, and Luciana Bianchi15

1 Department of Astronomy, University of Washington, Box 353222, Seattle, WA 98195-3224, USA
2 McWilliams Center for Cosmology, Department of Physics, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA, USA
3 Padova Astronomical Observatory, Vicolo dell’Osservatorio 5, Padova, Italy
4 Raytheon, Tucson, AZ 85726, USA
5 Steward Observatory, University of Arizona, Tucson, AZ 85726, USA
6 Astronomy Department, University of California, Berkeley, CA 94720, USA
7 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
8 Department of Astronomy, University of Michigan, 323 West Hall, 1085 S. University Ave., Ann Arbor, MI 48105-1107, USA
9 University of Alberta, Department of Physics, 4-183 CCIS, Edmonton AB T6G 2E1, Canada
10 Minnesota Institute for Astrophysics, 116 Church Street SE, Minneapolis, MN 55455, USA
11 Johns Hopkins University, STScI, 7500 San Martin Drive, Baltimore, MD 21218, USA
12 University of Utah, Salt Lake City, UT 84112, USA
13 University of California—Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA
14 National Optical Astronomy Observatory, P.O. Box 26732, Tucson, AZ 85726, USA
15 JHU, 430 North Charles St., 473 Bloomberg Center for Physics and Astronomy, Baltimore, MD 21218, USA

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Abstract

We present panchromatic resolved stellar photometry for 22 million stars in the Local Group dwarf spiral Triangulum (M33), derived from Hubble Space Telescope observations with the Advanced Camera for Surveys in the optical (F475W, F814W), and the Wide Field Camera 3 in the near-ultraviolet (F275W, F336W) and near-infrared (F110W, F160W) bands. The large, contiguous survey area covers ~14 square kpc and extends to 3.5 kpc (14′, or 1.5–2 scale lengths) from the center of M33. The PHATTER observing strategy and photometry technique closely mimics that of Panchromatic Hubble Andromeda Treasury, but with updated photometry techniques that take full advantage of all overlapping pointings (aligned to within <5–10 milliarcseconds) and improved treatment of spatially varying point-spread functions. The photometry reaches a completeness-limited depth of F475W~28.5 in the lowest surface density regions observed in M33 and F475W~26.5 in the most crowded regions found near the center of M33. We find the young populations trace several relatively tight arms, while the old populations show a clear, looser two-armed structure. We present extensive analysis of the data quality, including artificial star tests to quantify completeness, photometric uncertainties, and flux biases. This stellar catalog is the largest ever produced for M33, and is publicly available for download by the community.

Unified Astronomy Thesaurus concepts: Triangulum Galaxy (1712); Stellar populations (1622); Local Group (929); Multi-color photometry (1077); Celestial objects catalogs (212)

Supporting material: machine-readable tables

1. Introduction

Resolved stellar photometry has the potential to constrain fundamental processes in astrophysics, including star formation, stellar evolution, feedback into the interstellar medium, galaxy formation and evolution, and chemical enrichment. The stars themselves are the fossil record of these processes, which leave signatures in the properties of individual stars, their mass distribution, their distribution of colors and magnitudes, and their spatial distribution with respect to other galactic tracers.

While Gaia is transforming our understanding of the stars and structure of the Milky Way disk (Gaia Collaboration et al. 2018), we still need comparably detailed population studies of other disks to put our Galaxy and its stellar populations in context. The best targets for such studies are the galaxies in the Local Group, which contains two spirals other than the Milky Way—M31, a “green valley” Sb galaxy, and M33, a blue sequence, star-forming dwarf spiral. Along with the Milky Way, these two galaxies form our best anchors for baryonic processes in spiral galaxies. This set of three galaxies spans a large dynamic range, giving ample opportunities for contrasting how astrophysical processes are shaped by other parameters. For example, both M31 and our Galaxy are of similar mass and metallicity (Gregersen et al. 2015; Watkins et al. 2010), but M31 seems to have a much more dramatic recent merger history (e.g., D’Souza & Bell 2018; Hammer et al. 2018; Kruisjes et al. 2019).

In contrast to both of these more massive partners, M33 is of lower mass and metallicity, and appears to have a relatively quiescent merger history, as suggested by its inside-out growth (Magrini et al. 2007; Williams et al. 2009; Beasley et al. 2015; Mostoghiu et al. 2018) and lack of a significant extended stellar halo (McConnachie et al. 2010; McMonigal et al. 2016) or prominent thick disk (Wyse 2002; van der Kruit & Freeman 2011). Thus, M33 probes a different set of physical and chemical evolution properties than the other Local Group disk galaxies, and we can constrain these in exquisite detail through measurements of M33’s constituent stars.
Along with M31, previously surveyed with HST as part of the Panchromatic Hubble Andromeda Treasury (PHAT; Dalcanton et al. 2012), M33 is one of the richest galaxies in the Local Group for obtaining photometric measurements of resolved stars in a spiral galaxy. It is close enough that we can resolve stars all the way down to the ancient main sequence (Williams et al. 2009) over much of the disk. All of its stars are at the same distance and foreground extinction, alleviating issues related to the wide range of distances and extinctions of stars in the Galaxy. Furthermore, M33 has no well-established significant bulge component beyond its nuclear cluster (Kormendy & McClure 1993; McLean & Liu 1996), and at most a weak pseudobulge or bar (Regan & Vogel 1994; Minniti et al. 1993; Stephens & Frogel 2002; Corbelli & Walterbos 2007), meaning that there is little confusion between disk and bulge populations. The metallicity gradient in M33 is well known, and has been measured many times with planetary nebulae, asymptotic giant branch (AGB) stars, and H II regions (e.g., Cioni et al. 2008; Rosolowsky & Simon 2008; Magrini et al. 2009, 2010; Bresolin et al. 2010; Torbion San Cipriano et al. 2016; Lin et al. 2017). These studies have provided a range of measured central metallicities of 8.4 < $12 + \log(O/H) < 8.8$ and a range of slopes of $−0.05 < \text{dex/kpc} < −0.02$. Our representation in the right panel of Figure 1 is approximate and extrapolated based on these measurements, and shows how M33 covers the gap in metallicity between the LMC and M31. The star formation rate (SFR) density of M33 is significantly higher than in M31, making it an excellent probe of higher-intensity star formation environments. The total SFR from the GALEX far-UV (FUV) and Spitzer 24 $\mu$m observations is $\sim0.5$ $M_\odot$ yr$^{-1}$ (e.g., Verley et al. 2009), which is higher than the rate in the entire PHAT survey: $\sim0.3$ $M_\odot$ yr$^{-1}$ in an area about eight times larger (Lewis et al. 2015). These measurements are consistent with the order-of-magnitude relative difference in star formation intensity distributions shown in Figure 1.

M33’s value for obtaining knowledge about disk stellar populations is reflected in its rich history of resolved star studies, dating back to the 19th century (e.g., Roberts 1899). Since then, ground-based observations have studied the bright massive stars in great detail, providing estimates of star formation rate and constraints on the evolution of massive stars (e.g., Madore et al. 1974; Humphreys & Sandage 1980; Massey et al. 1996, and many others). The bright stars that can be resolved from the ground were finally fully cataloged by Massey et al. (2006), and its extended halo was probed by the Pan-Andromeda Archaeological Survey (PAndAS; McConnachie et al. 2010). More recent ground-based work focuses on the variability of these massive stars to further constrain their complex evolutionary stages (e.g., Gordon et al. 2016; Humphreys et al. 2017; Smith et al. 2020, and many others).

Over the past few decades, past ground-based studies of M33 have been supplemented with HST imaging, both farther into the ultraviolet (e.g., Chandar et al. 1999; Hoopes & Walterbos 2000) and to much fainter depth in the optical (e.g., Mighell & Rich 1995; Sarajedini et al. 2000; Barker et al. 2007a, 2007b; Williams et al. 2009). These capabilities have provided deep insight into the properties of the youngest and oldest stars and stellar clusters, as well as the formation processes of the M33 disk (e.g., van der Kruit & Freeman 2011, and references therein).

M33’s stellar population studies benefit from the legacy of surveys across virtually all wavelengths. Its cold interstellar medium (ISM) has been mapped through 21 cm maps of atomic HI (Deul & van der Hulst 1987; Gratier et al. 2010; Koch et al. 2018), through millimeter maps of molecular gas in the CO($J = 1 − 0$) and CO($J = 2 − 1$) lines (Figure 2; see, e.g.,}
Figure 2. Locations of the three M33 HST “bricks” (blue) compared to the FUV (background grayscale image, tracing unobscured star formation), Chandra (black outline, allowing detection of X-ray point sources), CO observations to show coverage (red contours), and Herschel FIR spectroscopy from the HerM33s survey (green) (Rosolowsky et al. 2007; Kramer et al. 2010; Xilouris et al. 2012; Mookerjea et al. 2016).

In this paper, we present first results from an equivalent high-resolution, six-band survey of M33, so that we may provide a resolved stellar photometry catalog with the same quality, giving the community the ability to probe the same processes in a galaxy with very different physical properties, including lower mass, lower metallicity, and higher star formation intensity. Once the stellar populations of both galaxies are measured in such exquisite detail, the power of direct comparison will likely lead to even more illuminating results. While this paper mainly presents the photometric catalogs and demonstrates the quality of the measurements, we anticipate a number of future dedicated papers on M33’s stellar populations and their connection to their host.

Herein, we describe our large HST survey of M33, PHATTER. Section 2 describes our observing strategy and data reduction techniques. Section 3 provides our results, including our final catalog of six-band panchromatic photometry of all of the stars detected in our investigations of the quality of the photometry in the catalog, and analysis of the luminosity function and artificial star tests (ASTs). Finally, Section 4 summarizes the paper. Throughout, we assume a distance to M33 of 859 kpc ($m − M = 24.67$; de Grijs et al. 2017).

2. Observations and Data Analysis

2.1. Observing Strategy

The highest-impact science we anticipate from the new M33 observations comes from exploring galactic environments that are distinct from other Local Group galaxies. Our observing strategy was therefore designed to make comparisons as straightforward as possible, by reproducing the observing strategy for M31, but targeting regions of M33 with complementary properties.

As shown in Figure 1, M33 is a lower-metallicity galaxy than most of M31 at the present day, and its inner regions nicely bridge the metallicity gap between the LMC and M31’s outer regions (similar gradient to, e.g., Cioni et al. 2008; Rosolowsky & Simon 2008; Magrini et al. 2009, 2010; de Grijs et al. 2010; Torbío San Cipriano et al. 2016; Lin et al. 2017). Those same inner regions of M33 also have a typical star formation rate intensity that is nearly a factor of 10 higher than in the area covered by the PHAT survey in M31, adding considerable leverage to studies of the interaction between stars and the ISM. We therefore targeted the new M33 observations on these inner regions, where there is also considerable multiwavelength coverage from other observatories—covering, for example, nearly all of the CO($J = 1 − 0$) molecular cloud detections from Rosolowsky et al. (2007), as shown in Figure 2.

We build up this survey area using the same PHAT tiling strategy, as described in Dalcanton et al. (2012). Observations are organized into “bricks” of 3×6 WFC3/IR footprints (Figure 3), with observations of each 3×3 half-brick taken ~6 months apart, after the telescope has rotated 180° (see Figure 3), with ORIENT=55 for one half-brick and 235 for the other. At each pointing, Wide Field Camera 3 (WFC3)/UVIS observations (F275W–250–300 nm, and F336W–310–360 nm filters) are taken in one orbit and WFC3/IR observations (F110W–900–1400 nm and F160W–1400–1700 nm filters) are taken in another, while the Advanced Camera for Surveys (ACS)/WFC operates in parallel, observing in F475W–400–550 nm and F814W–700–950 nm, covering the
Figure 3. WFC3/IR footprints of our M33 survey are plotted on a Sloan Digital Sky Survey (SDSS) image of M33. Brick 1 is marked by the 6 × 3 set of footprints surrounding the galaxy center. Brick 1 is the northernmost 6 × 3 footprints, and Brick 3 is the southernmost set. The field numbers for each brick are 1−18, where 1−6 are the top row from left to right, 6−12 are the next row down, etc. The orientation of Field 5 in Brick 2 was shifted due to a lack of available guide stars in the standard orientation, and Field 6 was shifted slightly to compensate.

Table 1

Sample Exposure Data for One Field

| Target Name        | R.A. (J2000) | Decl. (J2000) | Start Time   | Exp. (s) | Inst. | Aperture | Filter | Orientation |
|--------------------|--------------|---------------|--------------|----------|-------|----------|--------|-------------|
| M33-B01-F01-IR     | 01h34m33s    | +30°47'57"    | 2017-12-28 06:53:23 | 399.23   | WFC3  | IR-FIX   | F160W  | −80.3544    |
| M33-B01-F01-IR     | 01h34m33s    | +30°47'58"    | 2017-12-28 07:01:04 | 699.23   | WFC3  | IR-FIX   | F160W  | −80.3527    |
| M33-B01-F01-IR     | 01h34m33s    | +30°47'58"    | 2017-12-28 07:13:45 | 399.23   | WFC3  | IR-FIX   | F160W  | −80.3530    |
| M33-B01-F01-IR     | 01h34m33s    | +30°47'58"    | 2017-12-28 07:22:28 | 399.23   | WFC3  | IR-FIX   | F160W  | −80.3567    |
| M33-B01-F01-IR     | 01h34m33s    | +30°47'58"    | 2017-12-28 07:31:11 | 399.23   | WFC3  | IR-FIX   | F160W  | −80.3554    |
| M33-B01-F01-UVIS   | 01h34m33s    | +30°47'59"    | 2017-12-28 05:20:02 | 550.00   | WFC3  | UVIS-CENTER | F336W | −80.1842    |
| M33-B01-F01-UVIS   | 01h34m33s    | +30°47'59"    | 2017-12-28 05:31:49 | 350.00   | WFC3  | UVIS-CENTER | F275W | −80.1837    |
| M33-B01-F01-UVIS   | 01h34m34s    | +30°47'59"    | 2017-12-28 05:40:19 | 700.00   | WFC3  | UVIS-CENTER | F336W | −80.1838    |
| M33-B01-F01-UVIS   | 01h34m34s    | +30°47'58"    | 2017-12-28 05:54:37 | 540.00   | WFC3  | UVIS-CENTER | F275W | −80.1831    |
| M33-B01-F01-WFC    | 01h34m34s    | +30°47'51"    | 2017-07-27 22:08:21 | 15.00    | ACS   | WFC      | F814W  | −127.6122   |
| M33-B01-F01-WFC    | 01h34m34s    | +30°47'51"    | 2017-07-27 22:18:26 | 350.00   | ACS   | WFC      | F814W  | −127.6120   |
| M33-B01-F01-WFC    | 01h34m33s    | +30°47'51"    | 2017-07-27 22:26:56 | 700.00   | ACS   | WFC      | F814W  | −127.6124   |
| M33-B01-F01-WFC    | 01h34m34s    | +30°47'51"    | 2017-07-27 22:41:14 | 430.00   | ACS   | WFC      | F814W  | −127.6123   |
| M33-B01-F01-WFC    | 01h34m34s    | +30°47'51"    | 2017-07-27 23:33:11 | 10.00    | ACS   | WFC      | F475W  | −127.6115   |
| M33-B01-F01-WFC    | 01h34m34s    | +30°47'51"    | 2017-07-27 23:40:10 | 600.00   | ACS   | WFC      | F475W  | −127.6114   |
| M33-B01-F01-WFC    | 01h34m34s    | +30°47'51"    | 2017-07-27 23:52:51 | 370.00   | ACS   | WFC      | F475W  | −127.6116   |
| M33-B01-F01-WFC    | 01h34m34s    | +30°47'51"    | 2017-07-28 00:01:39 | 360.00   | ACS   | WFC      | F475W  | −127.6116   |
| M33-B01-F01-WFC    | 01h34m34s    | +30°47'51"    | 2017-07-28 00:10:17 | 360.00   | ACS   | WFC      | F475W  | −127.6114   |

(This table is available in its entirety in machine-readable form.)
adjacent half-brick. When the telescope rotates orientations in ∼6 months, the primary WFC3 observations cover the area of the original ACS parallels, and vice versa. Note that this produces a time difference between the optical and UV + IR observations, which may produce unusual colors for time-varying sources. Observations for this program (GO-14610) were taken between 2017 February 21 and 2018 February 25. The downloaded calibrated images used for photometry were processed under OPUS versions 2016_2-2017_3b. For ACS/WFC and WFC3/UVIS, we start with the charge transfer efficiency (CTE)-corrected (Anderson & Bedin 2010; Anderson & Ryon 2018), . for WFC3/IR, we start with flat image files.

We chose a three-brick mosaic to maximize coverage of the regions of high star formation intensity and existing CO detections (Figure 3). Brick 1 is the 3 × 6 array covering the northern portion of the galaxy, Brick 2 covers the center, and Brick 3 is to the south. Within each brick, each WFC3/IR pointing area is given a field number, with Field 1 being the upper left on Figure 3 and Field 18 being the lower right. ACS observations are labeled with the WFC3 field that they overlap. Of the 54 pointings, one field (Brick 2, Field 5) had no guide stars available in the desired orientation, and was therefore rotated slightly to make observations possible. This change led to a slight (∼20″) gap in coverage at the northwest corner of Brick 2 (01:33:30, 30:44:00). In total, the survey area tiled the inner 12′ × 19.8′ (3.1 × 4.6 kpc, projected; 4.3 × 4.6 kpc, deprojected) of M33, extending to roughly ∼1.6 disk scale lengths, assuming a 6″ scale length (Regan & Vogel 1994).

We adopted an exposure sequence (Table 1) and dithering strategy identical to those in PHAT, with the only significant change being switching to using UV pre-flash to minimize CTE losses in WFC3/UVIS (FLASH = 10 for F336W and = 11 for F606W).
F275W). WFC3/IR exposures were taken with 13 MULTI-ACCUM nondestructive read samples of the STEP100 sequence for a single F110W exposure, three F160W exposures with nine samples of the STEP200 sequence, and one additional F160W exposure with ten samples of the STEP100 sequence. The adopted dithers are designed to produce Nyquist sampled images in F475W, F814W, and F160W, but do not fill in the ACS chip gap. Instead, the ACS chip gaps are filled by overlapping exposures from observations in adjacent fields. The two WFC3/UVIS exposures for each filter are dithered to fill the chip gap, but they have challenging cosmic ray rejection, due to having only one to two overlapping images. The ACS observations also include very short “guard” exposures in F475W (10 s) and F814W (15 s) to capture photometry for the brightest stars, which can be saturated in the longer individual exposures. A table of the exposures at each position is supplied in Table 1.

The resulting map of exposure times in all cameras is shown in Figure 4. Notable features include the slightly larger WFC3/UVIS fields of view, which lead to larger rectangular overlaps between adjacent fields than the minimally overlapping WFC3/IR fields, and the diagonal overlaps of the even larger ACS/WFC exposures. Some of the inconsistencies in the tiling pattern are due to adjustments that ensured coverage with the nonstandard Brick 1, Field 5 rotation. The most highly overlapped regions in F475W and F814W have over 30,000 seconds of total exposure time. However, because the majority of observations in the optical and IR are crowding-limited, rather than photon-limited, the varying exposure times due to the overlapping pointings tend to affect the measured source density in less obvious ways that are often only noticeable at faint magnitudes.

2.2. Photometry

We measured point-spread function (PSF) fitting photometry on the location of every star detected in our survey footprint on every exposure that covered the position of the star. We closely followed the process used for the PHAT survey photometry, in order to simplify comparisons; however, there have been some improvements made to the process, based on lessons learned from PHAT.

The first improvement was the use of CTE corrected (flic-type) for photometry. In PHAT, no correction was used for WFC3/UVIS photometry, and ACS/WFC photometry was corrected at the catalog level. This change was implemented to address systematic uncertainties that appeared to be related to CTE in Williams et al. (2014) at the faint end. In addition, we implemented spatially varying TinyTim PSFs (Krist et al. 2011) for all cameras, to address the systematic uncertainties that appeared to be related to the PSF in Williams et al. (2014). All of these changes affect the photometry at the $\lesssim 0.1$ mag level, but may help to mitigate systematics related to position on the detector.

A high-level overview of the process of measuring the stellar photometry is provided as follows. The first step was the astrometric alignment of all 972 individual exposures with the Gaia catalog. These images were then combined into mosaic images, which were used for identifying and flagging bad pixels and pixels affected by cosmic rays for masking during photometry, as well as for public release images. The aligned individual images were processed with the DOLPHOT software package (Dolphin 2000, 2016) in order to measure PSF corrections and aperture corrections, which largely correct for variations in telescope focus. All overlapping individual exposures were stacked in memory, to search for all statistically significant detections using the full survey depth. At each detected centroid, the appropriate PSF was fit to the detection’s locations in each of the overlapping exposures, for all filters simultaneously. DOLPHOT then reported the measured fluxes and corresponding magnitudes in each image, as well as the combined flux and magnitude in each observed band. Finally, the raw photometry output was processed to flag possible artifacts and generate summary catalogs containing a subset of the many thousands of columns required to describe the complete measurement suite.

We describe each of these steps in detail below.

2.2.1. Astrometric Alignment & Mosaicking

We aligned all flc (ACS/WFC, WFC3/UVIS) and flt (WFC3/IR) images to the Gaia DR2 astrometric solution following the workflow presented by Bajaj (2017). Using this workflow, a reference astrometric catalog was retrieved from the Gaia archive with astroquery (Ginsburg et al. 2017, 2019), which was then passed to the TweakReg function in the Drizzlepac package (STSCI Development Team 2012; Hack et al. 2013; Avila et al. 2015), which finds centroids in each image, matches triangular patterns, and updates the image headers with the resulting aligned astrometric solution. The catalogs from which the final alignment solution was derived typically contained several hundred stars per ACS/WFC pointing, and 50–200 stars per WFC3/UVIS or WFC3/IR pointing.

The rms dispersions of the alignment residuals in $X$ and $Y$ are shown for all frames in Figure 5. Typical overall residual

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16 https://hubblesite.org/image/4305/gallery
17 https://github.com/spacetelescope/gaia_alignment
dispersions are on the order of 3 mas for ACS/WFC and WFC3/UVIS, and 7 mas for WFC3/IR. We used the AstroDrizzle function of the Drizzle-pac package (STSCI Development Team 2012; Hack et al. 2013; Avila et al. 2015) to combine the images within each band into a distortion-corrected, high-resolution pixel array (0.035/pixel in all bands, combined with a lanczos3 kernel). This higher-resolution array allows the full camera resolution to be recovered from dithered images, which were Nyquist sampled in F475W, F814W, and F160W. A minmed filter flagged statistical outlier pixels on the input exposures for all filters except F110W, for which there is only a single exposure, forcing us to rely on up-the-ramp fitting to flag bad pixels and filter cosmic rays. These pixels were not considered when generating the combined image, and they can easily be masked in any further analysis using those exposures. The flagged images were then combined with astrodrizzle, weighted by exposure time to produce deep mosaics that take advantage of subpixel dithering to improve spatial resolution.

An example of the improvements in depth and resolution is shown in Figure 6. The final product from the F475W exposures, which is the deepest band with the most subpixel dithers, was then applied as the astrometric reference image for all of the photometry measurements, including the positions of centroids measured in other bands but not detected in the F475W data.

2.2.2. Preparing Individual Exposures

After updating data quality extensions of the individual exposures in the astrodrizzle step, we further prepared the individual exposures for photometry with DOLPHOT. This preparation starts with running the task acsmask or wfc3mask (depending on camera) on each exposure. This task masks the flagged pixels in the DQ extensions of each CCD in each exposure, and multiplies the image by the appropriate pixel area map in order to take into account the effects of distortion on the flux measured in each pixel. We also run this step on the full-depth F475W combined image, which serves as the astrometric reference image for the final photometry. DOLPHOT uses this image as the astrometric reference frame to which all of the individual exposures will be aligned in memory, and from which all of the final star positions will be reported. As such, it is beneficial to use the deepest and highest spatial resolution image for this purpose.

We then ran the splitgroups task to produce separate files for each CCD of each exposure, and then we ran
of CCD reads in order to determine and record the parameters that align each individual frame to the astrometric reference image.

### 2.2.3. Running DOLPHOT on Full Image Stacks

With images, alignment parameters, PSF corrections, and aperture corrections for each individual exposure in hand, we could run full-stack photometry on any region of the survey. We ran these stacks using the DOLPHOT parameters updated from those of the PHAT survey in order to optimize the resulting catalogs for stellar populations science. The main updates are the removal of catalog-level CTE corrections, because we used the on-image CTE corrections (fic images), and the use of TinyTim PSFs for all cameras and filters. Values of all of the adopted DOLPHOT parameters for our reductions are provided in Table 2.

Memory and time limitations prevent us from simply putting the entire set of M33 exposures into DOLPHOT simultaneously. Instead, we subdivided the data into separate stacks to measure the photometry of different regions of the survey in parallel. We used DOLPHOT parameters that allow the user to define the region within which it performs photometry to launch multiple photometry processes, each with a different region of the survey including all overlapping individual images. We made these regions sufficiently small that DOLPHOT could complete the PSF fitting photometry in a reasonable amount of clock time, typically about one week. We set up 54 separate processes, each covering ~4 square arcminutes of the survey area, overlapping by 100 pixels on a side in order to avoid introducing edge effects. We then merged the resulting catalogs along the centers of the regions’ overlaps, to produce one final catalog for the survey. We then checked for any edge effects from the survey division by plotting the densities of stars. Such a plot is shown in Figure 7, which shows our measurement of completeness- and reddening-independent stellar density using the bright end of the red giant branch (RGB) in our reddest band (number of stars with 19.7 < F160W < 20.7 per square arcsecond). While this is our adopted standard for measuring stellar density, such maps made without such strict magnitude limits also show no edge effects related to our division used for processing.

### 2.2.4. Flagging and Processing Photometry Output

DOLPHOT returns a comprehensive table of all of the measurements made on every PSF fit to every image, as well as the combined measurement of every source in every filter. These measurements include the flux, Vega system magnitude, count-based uncertainty, signal-to-noise ratio, and several measurements of how well the source was fitted by the PSF. These quality metrics include sharpness, roundness, $\chi^2$, and crowding. Full descriptions of these are included in the DOLPHOT documentation.\(^\text{18}\) Briefly, the sharpness parameter measures how centrally peaked the source is compared to the PSF, or how much flux is concentrated in its central pixels relative to the outer ones. High values signify a source with high central concentration, such as a hot pixel or cosmic ray. Low values indicate that the source is not peaked enough, as expected for blended stars or background galaxies. The roundness parameter measures how circular the source is.

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\(^{18}\) http://americano.dolphinsim.com/dolphot/
zero is perfectly round, and \( \chi \) provides an estimate of the overall goodness of fit to the PSF. The crowding parameter measures how much the source’s photometry is affected by neighboring sources. The larger the crowding value, the more densely packed the PSF radius is with other sources, and the more likely it is that the reported magnitude has systematic uncertainties due to subtraction of neighbors.

For the PHAT survey, we determined values for the DOLPHOT parameters that tend to indicate good measurements of real stars (Williams et al. 2014). We have adopted these criteria for this catalog as well, and list them here for convenience. For a complete description of how they were determined, see Williams et al. (2014). They are different for each camera, as the pixel scale and PSF sampling were different, with the exception of the signal-to-noise ratio, for which we require \( S/N > 4 \) for all cameras. For ACS, the other parameters are: \( \text{sharpness}^2 < 0.2 \) and \( \text{crowding} < 2.25 \). For UVIS, they are: \( \text{sharpness}^2 < 0.15 \); and \( \text{crowding} < 1.3 \). For WFC3’s IR channel, they are: \( \text{sharpness}^2 < 0.15 \) and \( \text{crowding} < 2.25 \). These culling parameters were found to have the best balance of removing a high fraction of sources outside of color–magnitude diagram (CMD) features while keeping a very high fraction of total measurements. Thus, they lean toward being inclusive to avoid over-culling the data, at the expense of allowing a larger fraction of less certain measurements and contaminants.

We show the results of the above cuts on the CMD in Figure 8, where the stars that pass the metric make a CMD with well-defined, well-populated features, whereas the rejected stars form a relatively featureless cloud of points. However, there is always some risk in excluding important individual detections that did not produce high-quality PSF fits, such as bright stars in clusters. Thus, we include in our catalog all measurements, but we add a flag column to each band...
indicating whether it passes. This method allows the user to search the full catalog for a specific source, but also allows one to easily look at populations without being distracted by artefacts. For science cases that require a very clean sample, we recommend going to the full catalog and applying more conservative culling criteria than those adopted for our quality columns reported here.

The CMDs in all bands for the stars that pass our GST quality checks are shown in Figures 9–13. These figures also show, in the upper panels, the fraction of accepted measurements over the same CMD space.

In general, the highest impact of any metric on the culling of the data is that of the signal-to-noise ratio, which culls 100% of the measurements fainter than the detection limit in each band. However, in the IR, the quality metrics greatly reduce the amount of scatter in the CMD features at the faint end, as demonstrated by the low fraction of passing measurements up to 2 mag brighter than the detection limit in F160W in the crowded central regions. This difference is mainly attributable to the lower spatial resolution in the IR, which increases the impact of crowding, making more unreliable measurements that fall outside of the main features of the CMD.

We also show the effects of the depth in each band on our recovery of different features in Figure 14. Here, a representative subsample of stars is plotted on CMDs color-coded by the number of bands in which they were detected. It is clear from this figure that the UV observations are our shallowest, as nearly every UV detection is also detected in all of the other bands, and no RGB stars are detected in the UV. On the other hand, nearly every star in the catalog is detected in the optical, and all but the faintest main-sequence stars are detected in the IR. It is important to keep these depth effects in mind when working with the catalogs to perform analysis on the populations present in M33.

2.3. Artificial Star Tests

We quantify the accuracy, precision, and completeness of our photometry through ASTs, wherein artificial stars with known parameters are injected into the data and then recovered (if possible). ASTs place stars with realistic spectral energy distributions (SED) at a fixed sky position in each overlapping input image. We then put those images through the same photometry routine as the original data, and compare the output measurements for the star to the input values. If the star is not recovered by the photometry routine, that is also recorded. We repeat this process many thousands of times in many locations in the survey in order to characterize the quality of our photometry catalogs as a function of survey stellar density, where density is
the number of stars with \( 19.7 < F160W < 20.7 \) per square arcsec, which is also a proxy of galactocentric distance, as the stellar density falls off smoothly with radius. We describe each step in detail below.

We generated input artificial star magnitudes with MATCH (Dolphin 2002), using the fake utility to produce a simulated six-band photometric catalog sampled from the MIST model suite (Choi et al. 2016). We used two age bins, 1 Myr–1 Gyr

Figure 11. Same as Figure 9, but for all F475W and F814W measurements. Here, we split the measurements up by stellar density to show the effects of crowding. Stellar density range included in each CMD corresponds to the density maps shown in Figure 7, where density is the number of stars with \( 19.7 < F160W < 20.7 \) per square arcsec, and is marked in the upper right corner of each panel in units of stars per arcsec\(^2\). These bands are strongly affected by crowding, as apparent by the brighter magnitude limit at the higher stellar densities.
and 8 to 16 Gyr, and a metallicity range of $-2 < \text{[Fe/H]} < 0.5$, which together span sufficient color space to be applicable to the majority of our photometry. We restricted the optical magnitudes to $15 < F_{475W} < 31$ and $17 < F_{814W} < 30$, but left the UV and IR magnitudes effectively unconstrained. To ensure sufficient sampling of bright stars, we used a top-heavy IMF. CMDs of the final AST inputs are shown in Figure 15. For the purposes of assessing our photometric quality for each band, we performed tests that covered at least one magnitude beyond the full range of magnitudes passing our quality cuts in each band, but we did not cover the full range of detected colors. Full statistical modeling of the color distributions and

**Figure 12.** Same as Figure 11, but for the F475W and F160W measurements.
stellar SEDs will require more comprehensive ASTs, but these are sufficient for determining the completeness and precision as a function of magnitude in each of our observed bands. The results of these tests are supplied in Table 3, and described below.

We select four regions roughly along the major axis that span the full range of stellar densities, as shown in the right panel of Figure 7. For each region, we create input lists of 50,000 artificial stars with random XY locations, for a total of 200,000 ASTs. We run the stars from the input AST lists

Figure 13. Same as Figure 11, but for the F110W and F160W measurements.
through our photometry routine one at a time, such that the ASTs were not able to affect one another. DOLPHOT’s output in AST mode includes the location and flux of each input star, followed by all of the output that is reported for all of the unaltered data. Quality metrics that were used to flag measurements in the star catalog can then be applied to the AST catalog for consistency. While Table 3 reports all of the output measured magnitudes, for our quality analysis, we consider an artificial star to be “recovered” in a given band if it is within two reference frame pixels (0.07 arcsec) of the input source position and 1 mag of the input magnitude, and fulfills the GST (“good star”) quality requirements for said band discussed in Section 2.2.4. Figure 16 and Table 4 provide the completeness as a function of magnitude as well as the magnitude m_{50} at which 50% of inserted artificial stars are recovered (the “50% completeness limit”). For typical astronomical point sources, this completeness limit is largely set by the number of photons detected from an astronomical source. However, at high stellar densities, the completeness limit is set by the magnitude at which the surface density of sources (i.e., # of sources per square arcsec) is so high that they are always blended with brighter sources, rendering the original source undetectable. In this “crowding-limited” (rather than “photon-limited”) regime, the limiting magnitude is set more by stellar density than by photon counting statistics.

In both M31 and M33, HST imaging is crowding-limited in the optical and NIR over much of the disk, with the effects being most significant in the NIR, where the larger pixel scale and PSF size severely limit detection and reliable measurement of faint stars. In contrast, the PHAT and PHATTER observations in the UV bands are sufficiently shallow that they do not reach magnitudes where UV-detectable stars are so numerous that they begin to crowd together. For M33, the UV observations reach F275W ∼ 24.5 relatively independent of stellar density (or galactocentric distance), as expected for photon-limited images, whereas for the optical, the depth changes by ∼1.3 mag, moving from the inner to outer disk, reflecting the role that stellar crowding plays in setting the detection limit. In addition, the variation in completeness with magnitude (Figure 17) is qualitatively different in the photon-limited and crowding-limited data. In the former, the completeness drops from near 100% to 0% over a narrow range in magnitude (∼1), whereas in the crowding-limited data, the roll-off in completeness is much more gradual with magnitude (∼2), such that stars begin to be “hidden” by crowding several magnitudes before the magnitude at which they disappear from the catalog. The slow roll-off in completeness is the result (in part) of the increasing odds that a star will fail the quality cuts with the increasing likelihood of it blending with a star of comparable flux.

As with completeness, photometric uncertainties reflect impacts from both photon-counting uncertainties and crowding. There are multiple contributors to photometric uncertainty and bias in crowded-field photometry, beyond the well-known...
Table 3
Sample Artificial Star Data

| R.A. (J2000) | Decl. (J2000) | F275W Out-in | S/N | GST | F336W Out-in | S/N | GST | F475W Out-in | S/N | GST | F814W Out-in | S/N | GST | F110W Out-in | S/N | GST | F160W Out-in | S/N | GST |
|--------------|---------------|-------------|-----|-----|-------------|-----|-----|-------------|-----|-----|-------------|-----|-----|-------------|-----|-----|-------------|-----|-----|
| 23.436616    | 30.647496     | 29.515      | −1.793 | 0.4 | F           | 27.248 | 0.037 | 1.7 | F           | 26.114 | 0.202 | 16.0 | T           | 24.538 | 0.223 | 22.8 | T           | 24.006 | 0.577 | 3.4 | F           | 23.406 | 0.377 | 10.3 | T           |
| 23.436644    | 30.647382     | 32.387      | 99.999 | 0.0 | F           | 30.107 | 99.999 | 0.0 | F           | 29.138 | 99.999 | 0.0 | F           | 27.682 | 99.999 | 0.0 | F           | 27.229 | 99.999 | 0.0 | F           | 26.719 | 99.999 | 0.0 | F           |
| 23.436657    | 30.647784     | 31.890      | 99.999 | 0.0 | F           | 30.294 | 99.999 | 0.0 | F           | 29.845 | 99.999 | 0.0 | F           | 28.666 | 99.999 | 0.0 | F           | 28.315 | 99.999 | 0.0 | F           | 27.893 | 99.999 | 0.0 | F           |
| 23.436664    | 30.647719     | 27.948      | 99.999 | 0.0 | F           | 27.244 | 99.999 | 0.0 | F           | 27.176 | 99.999 | 0.0 | F           | 26.664 | 99.999 | 0.0 | F           | 26.540 | 99.999 | 0.0 | F           | 26.373 | 99.999 | 0.0 | F           |
| 23.436685    | 30.647769     | 24.387      | 0.413 | 4.7 | T           | 24.706 | −0.100 | 10.9 | T           | 25.494 | 0.107 | 31.9 | T           | 25.688 | 0.362 | 8.1 | T           | 25.826 | 99.999 | −0.9 | F           | 25.886 | 99.999 | −0.4 | F           |
| 23.436758    | 30.647418     | 21.550      | 0.047 | 48.4 | T           | 22.045 | 0.024 | 73.0 | T           | 23.471 | 0.010 | 137.1 | T           | 23.727 | 0.027 | 53.8 | T           | 23.943 | 0.149 | 9.3 | T           | 24.036 | 1.652 | 1.8 | F           |
| 23.436774    | 30.647546     | 27.575      | −1.026 | 1.3 | F           | 26.345 | 0.319 | 2.8 | F           | 26.029 | 0.141 | 19.3 | T           | 25.247 | −0.004 | 17.7 | T           | 25.043 | −0.292 | 5.9 | T           | 24.795 | 1.111 | 1.3 | F           |
| 23.436885    | 30.648781     | 32.132      | 99.999 | 0.0 | F           | 30.002 | 99.999 | 0.0 | F           | 29.102 | 99.999 | 0.0 | F           | 27.633 | 99.999 | 0.0 | F           | 27.156 | 99.999 | 0.0 | F           | 26.607 | 99.999 | 0.0 | F           |
| 23.436838    | 30.648715     | 22.383      | −0.011 | 31.9 | T           | 22.401 | 0.031 | 58.7 | T           | 22.796 | −0.009 | 197.2 | T           | 22.919 | −0.023 | 114.8 | T           | 23.000 | −0.014 | 31.8 | T           | 23.043 | −0.143 | 22.3 | T           |
| 23.436847    | 30.648508     | 21.232      | 0.030 | 55.6 | T           | 21.679 | 0.013 | 88.2 | T           | 23.026 | −0.008 | 192.8 | T           | 23.246 | −0.008 | 87.6 | T           | 23.441 | 0.148 | 12.8 | T           | 23.524 | 0.334 | 6.7 | T           |

(This table is available in its entirety in machine-readable form.)
impact of photon-counting statistics for the source and sky. These effects include uncertainties and biases from deblending of neighbors and sky estimation, as well as brightward biases from blending with undetected sources, which also increase the chance of detection. These effects are captured well by ASTs, though other systematic effects due to CTE or imperfect PSF models will remain. These various drivers of uncertainty and bias—crowding, exposure time, and background—all vary among filters and cameras, and thus will have different behavior in each.

We summarize the AST results for uncertainties and bias in Figure 18 and Table 5. Figure 18 shows the median difference in magnitude between the recovered and input magnitudes (recovered—input) as a function of input magnitude, and the 16th and 84th percentile ranges for the distribution of differences, shown as solid and transparent lines, respectively, plotted for a range of mean local densities (different color lines, with darker, thinner lines indicating higher stellar densities). Positive values indicate sources that are recovered at fainter magnitudes than their true magnitudes. Table 5 compiles numerical measurements of the bias and uncertainty for different filters and source densities. The uncertainty is also reported in units of the DOLPHOT-reported photometric uncertainty, which is based entirely on photon-counting uncertainties. The measured scatter between the true and recovered magnitudes is typically ∼20% larger than the photon-counting uncertainty in the NUV, a factor of ∼4 larger in the optical, and a factor of ∼5 larger in the NIR.

Figure 18 shows that, as expected, both the bias and the measurement uncertainty increase toward fainter magnitudes, where photon-counting and crowding are worse. The biases are much smaller than the photometric uncertainties (typically by a factor of 2–4) at all but the very faintest limits, where very few sources would be recovered at all. At a fixed magnitude in the optical or NIR bands, the biases and uncertainties are larger in regions with higher source densities, due to the higher crowding. In the optical and NIR bands, as sources become intrinsically fainter, their measured fluxes tend to be biased toward brighter magnitudes, due to unresolved, overlapping sources boosting the inserted artificial star above the detection limit. These effects are somewhat more pronounced in the NIR, most likely due to the camera’s larger pixels and longer wavelengths producing lower-resolution images (see Figure 6) and thus larger impacts due to crowding. No corrections for these biases have been made to the catalog.

In the UV, the trend of increasing bias and uncertainty for fainter sources is similar to what is seen in the optical and the NIR. However, the variations with UV magnitude are largely independent of local source density, reflecting the lack of significant crowding except at the very highest density in F336W. Another notable difference is in the sign of the bias. Well before completeness begins to decline significantly, the bias begins to become substantial, but has the opposite sign as seen in the optical and NIR, such that measurements seem to be biased significantly faintward. The effect appears most consistent with a slightly high background measurement, since the bias induced from high sky subtraction would be very small for bright sources and increase for fainter source, as we see in the NUV photometry. A similar trend was seen in the W14 PHAT photometry study, and the speculation was that perhaps CTE effects were causing the sky brightness to be overestimated. However, in this work we have used pre-flashed, CTE-corrected UVIS images, which should have reduced CTE effects on the sky brightness. Nonetheless, it is clear that our technique is likely attributing too much flux to the sky in the NUV images. None of these biases have been corrected for in the catalog, although they can be accounted for using our ASTs.

### Table 4

Fifty Percent Completeness Limits by Stellar Density (Stars per Square Arcsecond)

| Density   | F275W | F336W | F475W | F814W | F110W | F160W |
|-----------|-------|-------|-------|-------|-------|-------|
| 0–0.15    | 24.44 | 25.63 | 27.65 | 26.77 | 25.62 | 24.95 |
| 0.15–0.3  | 24.43 | 25.53 | 27.20 | 26.49 | 25.09 | 24.55 |
| 0.3–0.6   | 24.42 | 25.54 | 26.96 | 26.17 | 24.55 | 23.88 |
| 0.6–0.9   | 24.37 | 25.43 | 26.41 | 25.65 | 23.96 | 23.27 |
| 0.9+      | 24.14 | 25.10 | 25.75 | 25.23 | 23.56 | 22.91 |

Figure 16. Magnitudes at which we measure 50% completeness by stellar density in all filters. Stellar density corresponds to the maps in Figure 7, where density is the number of stars with 19.7 < F160W < 20.7 per square arcsecond; specifically, the right-hand panel is binned to complement the data points in this plot. Completeness limits in the UV are largely consistent over the full density range of the survey, whereas they grow brighter with increasing density in the optical and NIR due to crowding.

### 3. Results

Tables 6 and 3 provide samples of the photometry catalog and AST results from the survey. The catalog included here contains the positions, magnitudes, signal-to-noise ratio, and data quality flag for each detected star. While this table contains all of the stars detected and measured by DOLPHOT, not all of those measurements are likely to be stars in M33 with reliable photometry. To simplify the use of this version of the catalog, we have supplied a flag column (GST) for each band. This flag is set to “T” for sources that pass our quality checks detailed in Section 2.2.4, and to “F” for sources that do not. If a source has a T in any band, it is likely to be a real star in M33. However, it still may have “F” flags in other bands, indicating that the star was not reliably measured in that band. Only sources with “F” values in all bands are unlikely to be stars in M33.

Many of the stars in our catalog, as is the case for a large fraction of stars, are likely to be binary systems (e.g., Niu et al. 2020). At the distance of M33, we are not able to resolve binary stars such that our photometry contains the light of both...
members. However, the impact of binary stars varies by phase of stellar evolution. Many of the stars in our catalog are in the red giant phase, which is a short-lived and very bright phase of stellar evolution in the life of a relatively low-mass star. The binary companions of almost all of these stars are not red giants, and instead are faint, low-mass stars contributing insignificantly to the measured flux. In contrast, the more massive stars that make up the bright main sequence are more likely to have bright companions of similar mass (e.g., Kobulnicky & Fryer 2007). The companions of these stars will affect their photometry by contributing as much as half of the measured flux and should be considered when modeling photometry of upper main-sequence stars in our catalog.

The comprehensive (and much larger) catalog is available as a high-level science product (HLSP) in the Multimission archive via doi:10.17909/t9-ksyp-na40. This comprehensive catalog includes the combined measurements of each star in each band, as well as in each of the individual measurements in all of the survey exposures, along with all of the measurement quality information reported by DOLPHOT (uncertainty, \(\chi\),

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**Figure 17.** Photometric completeness (fraction of input stars that pass quality cuts) as a function of input magnitude in all filters for five characteristic density bins (labeled in upper right corners, where density is the number of stars with 19.7 < F160W < 20.7 per square arcsecond). Shaded regions show 95% confidence using the Jeffreys interval.
sharp, round, crowd, error flag). This catalog includes thousands of columns, and is hundreds of gigabytes in size.

The simplified AST results (with limited columns) in Table 3 are the location, input magnitude, output magnitude, output signal-to-noise, and output quality flag for each artificial star. The full catalog with all of the columns includes the input counts into each individual exposure, as well as all of the output photometry measurement columns as for the detected stars in the survey. As such, the HLSP catalog again is much larger and contains thousands of columns for those who would make use of the full AST input and output.

### 3.1. Color–Magnitude Diagrams

In Figure 8, we plot the entire catalog of detections in the optical bands, and we label the strongest features. The left panel shows all of the measurements, and the right panel shows the measurements that do not pass our quality metrics. The vast majority of these failed measurements are located at the faint end, where spurious and blended measurements are much more likely, while the few brighter ones are most likely contaminants and artifacts. This overview CMD shows the high fidelity of the photometry, which produces well-populated and clearly...
Table 5
Sample Photometric Bias, AST-derived Uncertainty, DOLPHOT-Reported Uncertainty, and AST/DOLPHOT Uncertainty Ratio and Stellar Density

| Density  | Filter | Magnitude | Bias   | Uncertainty | DOLPHOT | Ratio   |
|----------|--------|-----------|--------|-------------|---------|---------|
| 0–0.15   | F275W  | 17.5      | −0.003858 | 0.004518 | 0.003984 | 1.134049 |
| 0–0.15   | F275W  | 18.0      | −0.001987 | 0.005048 | 0.004971 | 1.015534 |
| 0–0.15   | F275W  | 18.5      | −0.000040 | 0.006076 | 0.005993 | 1.013889 |
| 0–0.15   | F275W  | 19.0      | 0.002106  | 0.007913 | 0.007987 | 0.990811 |
| 0–0.15   | F275W  | 19.5      | 0.006055  | 0.010892 | 0.009997 | 1.089572 |
| 0–0.15   | F275W  | 20.0      | 0.009879  | 0.014001 | 0.012977 | 1.078916 |
| 0–0.15   | F275W  | 20.5      | 0.015065  | 0.017544 | 0.015974 | 1.098268 |
| 0–0.15   | F275W  | 21.0      | 0.023059  | 0.023446 | 0.021009 | 1.115996 |
| 0–0.15   | F275W  | 21.5      | 0.034013  | 0.033485 | 0.028010 | 1.195487 |
| 0–0.15   | F275W  | 22.0      | 0.043005  | 0.045021 | 0.039973 | 1.126294 |
| 0–0.15   | F275W  | 22.5      | 0.064932  | 0.064028 | 0.055000 | 1.164144 |
| 0–0.15   | F275W  | 23.0      | 0.088065  | 0.092049 | 0.076996 | 1.195507 |
| 0–0.15   | F275W  | 23.5      | 0.137023  | 0.131494 | 0.114016 | 1.153292 |
| 0–0.15   | F275W  | 24.0      | 0.167010  | 0.171251 | 0.160019 | 1.070193 |
| 0–0.15   | F275W  | 24.5      | 0.142983  | 0.209921 | 0.207011 | 1.014055 |
| 0–0.15   | F275W  | 25.0      | −0.050442 | 0.239546 | 0.234015 | 1.023635 |

Note. Density = stars with 19.7 < F160W < 20.7 per square arcsecond. (This table is available in its entirety in machine-readable form.)

The high definition of these features, described below, suggests that a very large fraction of our photometry is reliable.

On the blue edge, the vertical plume of the upper main sequence (MS) is narrow and confined to a sharp edge determined by the saturation of color when the effective temperature of stars reaches hotter than \( \sim 10^4 \) K. Slightly to the red of this is a second, less populated blue plume that is the blue helium-burning (BHeB) sequence. This sequence marks the bluest extremity of the loop that characterizes the core-helium-burning phase of stars of intermediate and high masses. Its continuous appearance suggests that M33 has been forming stars at a relatively high intensity for hundreds of Myr.

The next bright plume to the red (brighter than F814W \( \sim 20 \) and starting at F475W–F814W \( \sim 2 \)) is the red helium-burning (RHeB) sequence. This feature consists of massive stars in the initial stage of core helium burning, with convective envelopes, before the decrease in the central helium content that drives their move toward the blue BHeB. It also contains the stars at the very latest phases of core helium burning; these stars move to the red again as their He-exhausted cores contract and extended convection sets in their envelopes. In theory, this RHeB sequences extends down in the CMD until it merges with the red clump (RC) of low-mass core-helium-burning stars at F814W \( \sim 25 \). The width of the color gap between the RHeB and the BHeB is sensitive to the metallicity, as more metal-rich stars will be redder during this phase. These sequences (MS, BHeB, and RHeB) are all indicative of recent star formation, and their numbers are consistent with the much higher star formation rate density in M33 relative to M31. For example, our catalog has \( \sim 30\% \) more OB stars (F336W–F475W < 0, \( M_{F475W} < 0 \)) than the entire PHAT catalog (\( \sim 300,000 \), versus \( \sim 230,000 \) in PHAT), resulting in a factor of 10 larger density of these young stars in M33 than in M31. Maps of recent star formation history, similar to those for M31 (Lewis et al. 2015), are in preparation. The cloud of stars redward of the RHeB consists of AGB stars that have expanded to be so large and cool that they become very bright and very red. The brightest among these stars can undergo extreme mass loss and develop dusty circumstellar shells, making them extend to fainter and extremely red optical colors. Below the AGB is the familiar RGB of evolved shell-hydrogen-burning low-mass stars, extending from F814W \( \sim 21 \) down through the AGB bump and red clump (RC) to the subgiants at F814W \( \sim 26 \). The AGB bump is comprised of early AGB (EAGB) stars, which are low-mass stars that undergo a pause in evolution when forming their double-shell structure (Gallart 1998). Below the AGB bump is the prominent RC of stable core-helium-burning low-mass stars. In addition, there is a small tail of stars departing from the RC toward the top left part of the CMD, which we tentatively identify as blends of RC plus MS stars, either because they are crowded together or are real binaries. Tails of reddened stars depart from the most prominent features, namely the RC and AGB bump, along the reddening vector, reflecting spreads in the internal extinction that often exceed half a magnitude in the V band. We compare our photometry to ground-based photometry of the same region from LGGS (Massey et al. 2006) and PAndAS (McConnachie et al. 2018) in Figure 19. Compared to ground-based imaging, our catalog extends 3–5 magnitudes deeper, has three orders of magnitude more stars (22 million versus \( \sim 70,000 \) in both LGGS and PAndAS), and has qualitatively more and tighter features. This comparison clearly demonstrates the improvement in available photometry and the power of HST to resolve stars in the M33 disk.

3.2. Star Clusters

The PHATTER data are able to resolve individual stars within star clusters in M33, allowing detailed age and metallicity studies. We show a few examples of young stellar clusters of a range of masses in Figure 20, all of which were identified by citizen scientists as part of the Local Group Cluster Search on Zooniverse (Johnson 2019; Wainer et al. 2020). The lower panels of this figure show zoomed-in F475W images of the clusters, and the upper panels show

https://www.zooniverse.org/projects/kjohnso/local-group-cluster-search
## Table 6
Sample Photometric Data

| R.A. (J2000) | Decl. (J2000) | F275W | S/N | GST | F336W | S/N | GST | F475W | S/N | GST | F814W | S/N | GST | F110W | S/N | GST | F160W | S/N | GST |
|--------------|--------------|-------|-----|-----|-------|-----|-----|-------|-----|-----|-------|-----|-----|-------|-----|-----|-------|-----|-----|
| 23.340786    | 30.523476    | 29.160| 0.1 | F   | 26.679| 2.1 | F   | 26.791| 10.4| T   | 26.325| 7.2 | T   | 99.999| 0.0 | F   | 99.999| 0.0 | F   |
| 23.340794    | 30.523207    | 23.059| 11.2| T   | 23.230| 15.4| T   | 24.244| 48.6| T   | 24.062| 38.2| T   | 99.999| 0.0 | F   | 99.999| 0.0 | F   |
| 23.340808    | 30.523388    | 99.999| -2.2| F   | 99.999| -1.5| F   | 26.613| 11.9| T   | 24.796| 26.3| T   | 99.999| 0.0 | F   | 99.999| 0.0 | F   |
| 23.340814    | 30.523616    | 99.999| -0.5| F   | 99.999| -0.0| F   | 28.516| 2.5 | F   | 27.409| 3.0 | F   | 99.999| 0.0 | F   | 99.999| 0.0 | F   |
| 23.340824    | 30.523322    | 25.680| 2.2 | F   | 27.131| 1.5 | F   | 28.579| 2.1 | F   | 27.189| 3.4 | F   | 99.999| 0.0 | F   | 99.999| 0.0 | F   |
| 23.340825    | 30.523415    | 25.555| 2.1 | F   | 28.072| 0.7 | F   | 28.599| 2.3 | F   | 27.096| 3.5 | F   | 99.999| 0.0 | F   | 99.999| 0.0 | F   |
| 23.340839    | 30.523445    | 99.999| -0.4| F   | 99.999| -0.6| F   | 28.191| 3.2 | F   | 27.260| 3.3 | F   | 99.999| 0.0 | F   | 99.999| 0.0 | F   |
| 23.340845    | 30.523811    | 99.999| -1.7| F   | 28.635| 0.4 | F   | 27.973| 3.9 | F   | 26.840| 4.8 | T   | 99.999| 0.0 | F   | 99.999| 0.0 | F   |
| 23.340846    | 30.523475    | 99.999| -0.7| F   | 99.999| -0.9| F   | 99.999| -0.1| F   | 27.709| 2.0 | F   | 99.999| 0.0 | F   | 99.999| 0.0 | F   |

(This table is available in its entirety in machine-readable form.)
optical CMDs of the regions within the clusters’ radii. In all cases, the blue plume of main-sequence stars is visible, showing the young population of cluster stars. Moreover, the sequence on the CMD is more populated in the more massive, larger clusters, showing the quality of the resolved photometry. While photometry in the clusters does not reach the faintest magnitudes of the survey due to crowding, it is clear that the PHATTER catalog will be a powerful tool for future studies of resolved populations in star clusters in M33.

3.3. Population Maps

Because features on the CMD roughly correspond to distinct populations, we have generated maps of the stellar density within some of the most distinct CMD features. Figure 21 shows the portions of the CMD used to select MS (young), AGB (intermediate age), and RGB (old) populations. Figure 22 shows the density maps of each of these populations. As might be expected, the young population is highly structured and
largely traces the spiral arms, and the old population follows a smooth density gradient expected of a disk. Interestingly, the old and intermediate populations appear to show two faint arms, while the young population appears to trace out more. The structures suggest a long-lived two-armed density structure, along with other, more transient, short-lived arms.

The intermediate-age population is not as simple to interpret on its own. However, in Figure 23 we show a map of the ratio of AGB to RGB stars, along with a plot of the ratio as a function of distance from the M33 center. There is a clear radial trend showing a higher fraction of intermediate-age stars farther out in the disk. These maps thus confirm measurements in several previous works (e.g., Davidge 2003; Block et al. 2007; Verley et al. 2009) and are consistent with other indications of inside-out disk formation in M33 (e.g., Magrini et al. 2007; Williams et al. 2009; Beasley et al. 2015; Mostoghiu et al. 2018), demonstrating the potential for our catalog for future detailed population studies in M33. M33's structure as seen by PHATTER will be explored in detail in a future paper.

3.4. Luminosity Functions

While these initial qualitative evaluations of our photometry are promising, we now move into quantitative tests of the fidelity and consistency of standard CMD features to further assess the robustness and homogeneity of the catalog. Two features that are very well-suited to such quality checks are the tip of the RGB (TRGB) and the RC. By comparing the locations of these features in the luminosity function, as a
Figure 23. Left: Median-filtered spatial map of the ratio of AGB to upper RGB stars (see Figure 21). In this case, RGB stars were selected across the entire field with $q_{F160W} < 21$ (as opposed to the dual selection shown in Figures 21 and 22) to eliminate varying completeness as a source of uncertainty in the ratio. Large dotted ellipses show one of the radial annuli used for the averaging in the right panel (inclination, position angle, and central coordinates are from van der Marel et al. (2019) and references therein), while the small dashed ellipse shows the approximate orientation, axis ratio, and maximum scale of M33’s weak central bar (Corbelli & Walterbos 2007). Right: Average AGB/RGB ratio as a function of deprojected distance from the M33 nucleus in kpc. Estimated maximum scale of M33’s weak bar is shown for reference (~559 pc or 2.24). In both the map and radial profile, there is a distinct enhancement of AGB populations in M33’s outskirts relative to the center. This supports previous work (e.g., Davidge 2003; Block et al 2007; Verley et al. 2009) as evidence of M33’s “inside-out” star formation history (Williams et al. 2009; Mostoghiu et al. 2018).

Figure 24. Left: Optical CMD showing the selection regions used to measure the F814W magnitude functions for the tip of the red giant branch and red clump features. Right: Normalized F814W luminosity functions for the TRGB (top) and red clump (bottom) for 12 6′ × 6′ regions of the survey, with lines weighted by the number of stars per sample. We predict apparent TRGB and RC magnitudes using $M_{\text{TRGB}} = M_{\text{RC}} = -4.05$ (Beaton et al. 2018) and $M_{\text{TRGB}} = -0.22$ (Groenewegen 2008), with a distance modulus of $m - M = 24.67$ (de Grijs et al. 2017) and foreground extinction $A_{\text{F814W}} = 0.063$ (Schlafly & Finkbeiner 2011). Note the consistency of changes in the magnitude distributions with the predicted TRGB and RC across the entire survey.
function of position in the survey, we can ensure that any variations are smooth—and thus most likely related to gradients in the stellar population demographics (e.g., age and metallicity).

The left panel of Figure 24 shows the optical color–magnitude selection regions for the TRGB and the RC on a CMD of the entire survey. The upper right panel shows the F814W luminosity function, normalized by the total number of stars sampled, for stars in the color range 2.5 < F475W–F814W < 3.5 at F814W = 20.7 and 20.3 < F814W < 21.3 at several locations in the survey, which should be dominated by the metal-poor RGB that has a TRGB absolute magnitude of $F814W \sim -4.05 \pm 0.1$ (Beaton et al. 2018). We see that the function steepens at the TRGB, and that the TRGB at this color remains consistent to within $\sim 0.1$ mag over the survey, showing that the amount of systematic uncertainty over large areas is small. Furthermore, this TRGB magnitude is within the uncertainties of that expected for a foreground $A_{F814W} = 0.063$ (Schlafly & Finkbeiner 2011) and a distance modulus of 24.67 ± 0.07 (de Grijs et al. 2017), suggesting that our absolute photometric calibration is also accurate.

In the lower right panel of Figure 24, we show the F814W luminosity function for stars in the color range 1 < F475W–F814W < 2 at F814W = 25 and 23.5 < F814W < 25.5 at several locations to check the position of the RC. This can be compared to $M_{RC}^I = -0.22 \pm 0.03$ from Groenewegen (2008), which converts to $M_{RC}^I = 24.51$ at the distance and extinction of M33. The magnitude of the peak of the RC remains consistent to within 0.1 mag (24.51 ± 0.10), confirming that, even at much fainter fluxes, the systematic uncertainties over large areas are small. There is a hint of a small bias to brighter magnitudes in some regions, as evidenced by the slightly brighter peak in some samples. Some bias is expected, given the results of the ASTs at this magnitude, as shown in Figure 18. However, some of the variation could also be an effect of the stellar population gradient. A future detailed study of the feature will be required to definitively determine the origin of this variation.

3.5. Foreground and Background Contamination

Our catalog has a small amount of contamination from Milky Way foreground stars and from background galaxies. To estimate the severity of the foreground contamination, we produced model Galactic populations using the Trilegal software package (Girardi et al. 2005). The model suggests ~3400 foreground stars in our survey footprint with F160W < 26, with ~2200 of these having F475W < 28. Thus, our catalog of 22 million stars contains only <0.02% foreground contamination. This fraction increases to <0.1% for the five million stars that pass our cuts in at least two bands. However, in certain areas of color–magnitude space, it is important to be able to identify foreground features so that they are not confused with M33 populations. To aid in this

Figure 25. CMDs for the ~5000 foreground stars (black scatter points) predicted by the Trilegal Galactic model for this region of the sky at the depth of our survey, overlaid on the GST CMDs. While the densities of points are not comparable, because the GST CMDs are 2D histograms, the locations of the foreground stars relative to M33 CMD features are easier to see on the overlay.
The only highly visible foreground feature is the narrow bright plume of stars at F110W − F160W = 0.7 that is the shared color of virtually all of the foreground main-sequence stars in the IR. Interestingly, M33 has a well-populated RHeB feature that is vertical at F110W − F160W = 0.9. We have verified that the majority of stars in this feature are the same as those in the bright feature at F475W − F160W ∼ 5, which has no significant foreground equivalent. Thus, not only are the RHeB stars separated from the foreground in IR color, the foreground contamination in our catalog appears to be less than expected. To estimate the severity of the background contamination, we looked for color outliers that were blue in F475W−F814W compared to their F814W−F160W colors, which is similar to the combination used for star–galaxy separation in previous works, such as Robin et al. (2007). We found outliers from the stellar locus fell at F475W−F814W < 2.5 and F814W−F160W > 3. Only 7183 sources passing our quality criteria in the IR bands have such colors, corresponding to approximately 0.16% background contamination when taking the IR quality flags into account. The contamination drops to 1073 sources, and 0.025%, for sources passing our quality criteria in the IR and optical bands.

4. Conclusions

We have produced a catalog of resolved stellar photometry for 22 million stars in the field of M33 from 54 HST pointings covering the inner 3.1 × 4.6 kpc in six bands, including F275W, F336W, F475W, F814W, F110W, and F160W. The astrometry of this catalog is aligned to the Gaia DR2 astrometric solution to ∼5 mas. This catalog reaches $m_{F275W} = 24.5$, $m_{F336W} = 25$, $m_{F475W} = 28.5$, $m_{F814W} = 27.5$, $m_{F110W} = 26$, and $m_{F160W} = 25$, with a signal-to-noise limit of 4. Crowding causes the limiting magnitude to be brighter in the redder bands closer to the center of M33. This photometry will be studied in great detail by many future studies, such as the history of star formation in M33, the M33 star cluster population, the initial mass function of star clusters in M33, feedback between the stars and interstellar medium in M33, the dust content of M33, and many more.

We have performed many quality checks of the photometry, including ensuring that the tip of the RGB is consistent with previous distance measurements of M33, in addition to running suites of ASTs, where stars of known SEDs are put into the data and the analysis routine was rerun to assess the precision and completeness with which stars are recovered.

The simplified version of our results catalogs provided here will likely provide all of the information required for many science use cases; however, the exhaustive and complete outputs from our photometry measurements are available from the multimission archive HLSP.

The code used to generate the tables and figures in this paper (with the exception of Figures 1 and 2) is available at https://github.com/meredith-durbin/m33_survey_plots.

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Facilities: HST(ACS/WFC), HST(WFC3/IR), HST (WFC3/UVIS).

Software: Astropy (Astropy Collaboration et al. 2013, 2018), Astroquery (Ginsburg et al. 2017, 2019), Dask (Rocklin 2015; Dask Development Team 2016), DOLPHOT (Dolphin 2000, 2016), DrizzlePAC (TSCTI Development Team 2012; Hack et al. 2013; Avila et al. 2015), Matplotlib (Hunter 2007), NumPy (van der Walt et al. 2011; Harris et al. 2020), Pandas (McKinney 2010, 2011), Seaborn (Waskom et al. 2018), SciPy (Jones et al. 2001), Scikit-learn (Pedregosa et al. 2011), Vaex (Breddels & Veljanoski 2018a, 2018b).

ORCID iDs

Benjamin F. Williams https://orcid.org/0000-0002-7502-0597
Meredith J. Durbin https://orcid.org/0000-0001-7531-9815
Julianne J. Dalcanton https://orcid.org/0000-0002-1264-2006
Dustin Lang https://orcid.org/0000-0002-1172-0754
Leo Girardi https://orcid.org/0000-0002-6301-3269
Adam Smercina https://orcid.org/0000-0003-2599-7524
Andrew Dolphin https://orcid.org/0000-0001-8416-4093
Daniel R. Weisz https://orcid.org/0000-0002-6442-6030
Yumi Choi https://orcid.org/0000-0003-1680-1884
Eric F. Bell https://orcid.org/0000-0002-5564-9873
Erik Rosolowsky https://orcid.org/0000-0002-5204-2259
Evan Skillman https://orcid.org/0000-0003-0605-8732
Eric W. Koch https://orcid.org/0000-0001-9605-780X
Christina W. Lindberg https://orcid.org/0000-0003-0588-7360
Lea Hagen https://orcid.org/0000-0001-8918-1597
Carl D. Gordon https://orcid.org/0000-0001-5340-6774
Anil Seth https://orcid.org/0000-0003-0248-5470
Karoline Gilbert https://orcid.org/0000-0003-0394-8377
Paragta GuhaThakurta https://orcid.org/0000-0001-8867-4234
Tod Lauer https://orcid.org/0000-0003-3234-7247
Luciana Bianchi https://orcid.org/0000-0001-7746-5461

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