THE YOUNG STELLAR POPULATION OF THE NEARBY LATE-TYPE GALAXY NGC 1311*

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ABSTRACT

We have extracted point-spread-function-fitted stellar photometry from near-ultraviolet, optical, and near-infrared images, obtained with the Hubble Space Telescope, of the nearby (D ≈ 5.5 Mpc) SBm galaxy NGC 1311. The ultraviolet and optical data reveal a population of hot main-sequence (MS) stars with ages of 2–10 Myr. We also find populations of blue supergiants with ages between 10 and 40 Myr and red supergiants with ages between 10 and 100 Myr. Our near-infrared data show evidence of star formation going back ∼1 Gyr, in agreement with previous work. Fits to isochrones indicate a metallicity of Z ≈ 0.004. The ratio of blue to red supergiants is consistent with this metallicity. This indicates that NGC 1311 follows the well-known luminosity–metallicity relation for late-type dwarf galaxies. About half of the hot MS stars and blue supergiants are found in two regions in the inner part of NGC 1311. These two regions are each about 200 pc across, and thus have crossing times roughly equal to the 10 Myr age we find for the dominant young population. The luminosity functions of the supergiants indicate a slowly rising star formation rate (∼10^{-5} M_⊙ yr^{-1}) from ∼100 Myr ago until ∼15 Myr ago, followed by a strong enhancement (∼10^{-2} M_⊙ yr^{-1}) at ∼10 Myr ago. We see no compelling evidence for gaps in the star-forming history of NGC 1311 over the last 100 Myr, and, with lower significance, none over the last Gyr. This argues against a bursting mode, and in favor of a gasping or breathing mode for the recent star formation history.

Key words: galaxies: individual (NGC 1311) – galaxies: spiral – galaxies: stellar content – infrared: galaxies – ultraviolet: galaxies

Online-only material: machine-readable and VO tables

1. INTRODUCTION

The original formulation of the stellar population concept (Baade 1958) was driven by the realization that the ages and metallicities of Galactic stars were related to their kinematics. While Baade’s identification of the young, metal-rich disk stars as Population I, and the old, metal-poor halo stars as Population II was a crucial starting point, observations in the last half century have identified both old and metal-rich stellar populations associated with the inner parts of spheroids (e.g., Terndrup et al. 1991; Idiart et al. 2007) and young and metal-poor stellar populations associated with low-luminosity star-forming galaxies (e.g., Mateo 1998; Weisz et al. 2008) and with the outer parts of luminous disks (e.g., Zaritsky et al. 1994; MacArthur et al. 2004; Kudritzki et al. 2008). Understanding young, metal-poor stellar populations is an essential task in modern astrophysics, both because it allows us a fuller understanding of star formation and stellar evolution as a function of metallicity, and because it offers us potential insights into the nature of star formation in the early, low-metallicity universe.

Our understanding of stellar populations has received an enormous boost from our ability to obtain arcsecond (or better) resolution images in the ultraviolet (UV) and near-infrared (NIR). In the NIR, the last decade has shown the complementary power of large ground-based surveys (Paturel et al. 2003; Skrutskie et al. 2006) and higher-resolution Hubble Space Telescope (HST) Near-Infrared Camera and Multi-Object Spectrograph (NICMOS) data. In the UV, we are now seeing the benefits of combining insights from the large but moderate-resolution GALEX (Martin et al. 2005) database with high-resolution imaging from HST (e.g., Overzier et al. 2008). Imaging at HST resolution provides the opportunity to study resolved stellar populations out to distances of ∼10 Mpc. Broad wavelength coverage (UV through NIR) allows us to investigate the full history of star formation in nearby galaxies.

NGC 1311 is a very nearby (D ≈ 5.5 Mpc) but little-studied late-type (SBm) galaxy. Tully et al. (2006) identify it as a member of the 14 + 14 Association, a loose group dominated by the luminous spiral NGC 1313. Table 1 summarizes the basic properties of the system. NGC 1311 was a target in two broadband HST snapshot surveys (GO programs 9124 and 9824; Windhorst et al. 2002; Taylor et al. 2005; Taylor-Mager et al. 2007; and Section 2 below). As a result, a set of broadband images spanning a wide wavelength interval (0.3–1.6 μm) at subarcsecond resolution now exists for this galaxy. As NGC 1311 is quite nearby, its bright star clusters and luminous individual stars are detected as discrete sources. We can thus probe the spatially resolved star formation history of NGC 1311 by studying the broadband spectral energy distributions of its star clusters, its individual stars, and its unresolved light. Our results for the star clusters are presented in Eskridge et al. (2008). This paper is concerned with the individual luminous stars. We shall address the unresolved light in a future publication.

In Section 2, we briefly summarize the HST observational data. We present the observed properties of the luminous stars in Section 3, and our analysis of these observations in Section 4. We summarize our conclusions and discuss issues for further research in Section 5.

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2. OBSERVATIONAL DATA

The data for this study are a set of UV, optical, and NIR images obtained with the Wide-Field and Planetary Camera 2 (WFPC2) and NICMOS on board HST. We have WFPC2 images taken through the F300W, F606W, and F814W filters, and a NICMOS image taken with the NIC3 camera through the F160W filter. A summary of the observations is given in Table 2. The F300W image was obtained as part of the HST program GO-9124 “Mid-UV Snapshot Survey of Nearby Irregulars: Galaxy Structure and Evolution Benchmark” (PI: R. Windhorst). For this program, the centers of the target galaxies were placed on the WF3 chip. Details of the observing and reduction procedures for these data are given in Windhorst et al. (2002). The F160W image was obtained as part of the HST program GO-9824 “NIC3 SNAPs of Nearby Galaxies Imaged in the mid-UV: The Remarkable Cool Stellar Population in Late-Type Galaxies” (PI: R. Windhorst). Details of the observing and reduction procedures for these data are given in Taylor et al. (2005). The archival WFPC2 F606W and F814W images of NGC 1311 were obtained as part of the HST program GO-9162 “Local Galaxy Flows and the Local Mass Density” (PI: R. Tully). The WFPC2 Wide-Field Camera (WFC) spatial sampling is \( \approx 0.10 \) per pixel. The Planetary Camera (PC) spatial sampling is \( \approx 0.05 \) per pixel. No stars are detected in the F300W PC image, but we do use data from the PC in F606W and F814W. The NIC3 spatial sampling is \( 0.20 \) per pixel. We show images of the central \( 42'' \times 26'' \) of NGC 1311 in all four observed bands in Figure 1.

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Table 1

| Property         | Value       | References |
|------------------|-------------|------------|
| \( m_B \)        | 13.22 ± 0.21 | 1          |
| \( (B - V) \)    | 0.46 ± 0.02  | 1          |
| \( \log D_{25} \) | 1.48 ± 0.03  | 1          |
| \( \log R_{25} \) | 0.59 ± 0.05  | 1          |
| \( V_0 \)        | 568 ± 5 km/s | 2          |
| \( E(B - V) \)   | 0.07         | 3          |
| \( D \)          | 5.45 ± 0.08 Mpc | 4          |
| \( M_B \)        | -15.5       | 1,4        |
| \( S_{H_1} \)    | 15.4 Jy km/s | 2          |
| \( M_{H_1}/L_B \) | 0.46 \( M_{\odot}/L_{\odot} \) | 1,2,4    |
| EW(H\(\alpha\)+[N ii]) | 33 ± 2 Å | 5          |
| [N ii]/H\(\alpha\) | 0.08 | 5          |

References. (1) de Vaucouleurs et al. 1991; (2) Koribalski et al. 2004; (3) Schlegel et al. 1998; (4) Tully et al. 2006; (5) Kennicutt et al. 2008.
3. STELLAR PHOTOMETRY

We used HSTPho\textsuperscript{5} (Dolphin 2000) to extract point-spread-function-fitted stellar photometry from the WFPC2 images. HSTPho is designed to perform stellar photometry on WFPC2 images, including aperture corrections, charge-transfer efficiency (CTE) corrections, and zero-point calibrations. The zero-points to the VEGAMAG system are thus updated from those of Holtzman et al. (1995). For the NICMOS image, we first applied the nonlinearity correction determined by de Jong (2006). This refines the zero-point calibration from the 2004 June standard (Noll et al. 2004). We then extracted stellar photometry using the version of DAOPHOT (Stetson 1987) embedded in the XVISTA image analysis package (Stover 1988). For the NICMOS photometry, we had to determine the aperture correction manually by measuring the asymptotic count rates for two bright, isolated stars in the observed NIC3 image mosaic. The correction from a 2 pixel radius to infinite aperture is $0.10 \pm 0.02$ mag. All of our photometry is calibrated to the VEGAMAG system. We detect a total of 4369 stars in at least two bands. Table 3 shows our photometry for the first 10 objects in the sample. The full table is presented in the online edition of this paper. Column 1 gives a running ID number (in order of increasing right ascension). Columns 2 and 3 give the J2000.0 right ascension and declination determined from the WFPC2 WCS header information. Columns 4 and 7 give the WFC chip on which the star is found in the F300W and F606W/F814W observations, respectively. Columns 5 and 6 give the $X$ and $Y$ pixel positions of the star in the F300W image, Columns 8 and 9 give the F606W/F814W pixel positions, and Columns 10 and 11 give the NICMOS pixel positions. Columns 12–15 give the measured magnitudes (top row) and errors (bottom row) in F300W ($U_{300}$), F606W ($V_{606}$), F814W ($I_{814}$), and F160W ($H_{160}$). Columns 16–21 give the measured colors (top row) and errors (bottom row) in ($U_{300} - V_{606}$), ($U_{300} - I_{814}$), ($V_{606} - H_{160}$), ($V_{606} - I_{814}$), ($V_{606} - H_{160}$), and ($I_{814} - H_{160}$), respectively.

3.1. Completeness Tests

We conducted a series of artificial star tests on our images to determine both the completeness and accuracy of our photometry. For the WFPC2 images, we used the artificial star capability of HSTPho. For the NIC3 image, we used the version of DAOPHOT embedded in the XVISTA image analysis package. Figure 2 and Table 4 show our completeness fraction as a function of magnitude in all four bands. Our photometric accuracy is shown in Figure 3. Table 5 shows the mean offset and dispersion as a function of magnitude in all four bands. Our 50% completeness limits, in magnitudes, are 22.2 ($F_{300}$), 25.7 ($F_{606}$), 24.4 ($F_{814}$), and 20.2 ($F_{160}$). At these limits, the artificial star tests have offsets that are statistically equivalent to zero, and dispersions of 0.1–0.2 mag.

3.2. Color–Magnitude and Color–Color Diagrams

Figure 4 shows a suite of color–magnitude diagrams (CMDs) for the resolved stellar populations of NGC 1311. The long-dashed lines show the 50% completeness levels for the relevant bands. The star clusters studied by Eskridge et al. (2008) are not plotted. The $V_{606}$ versus ($V_{606} - I_{814}$) CMD shows two plumes of luminous stars, separated by about a magnitude in color. The dashed boxes in Figure 4(a) show the two regions of the CMD that we use to select the stars in these two plumes (hereafter the blue-plume and red-plume stars).

Inspection of Figure 4 allows us to make several qualitative statements about the resolved stellar populations. First, the

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\textsuperscript{5} We used the 2003 May revision of HSTPho v. 1.1.5b obtained from http://purcell.as.arizona.edu/wfpc2_calibv.
Table 3
Stellar Photometry

| ID  | RA (J2000.0) (hh:mm:ss.sss) | Decl (J2000.0) (dd:mm:ss.ss) | Chip | X$_{300}$ (pixel) | Y$_{300}$ (pixel) | Chip X$_{V}$ (pixel) | Y$_{V}$ (pixel) | X$_{NIC}$ (pixel) | Y$_{NIC}$ (pixel) | UV$_{500}$ (mag) | V$_{606}$ (mag) | I$_{814}$ (mag) | H$_{160}$ (mag) | UV$_{500}$–V$_{606}$ (mag) | UV$_{500}$–I$_{814}$ (mag) | UV$_{500}$–H$_{160}$ (mag) | V$_{606}$–I$_{814}$ (mag) | V$_{606}$–H$_{160}$ (mag) | I$_{814}$–H$_{160}$ (mag) |
|-----|---------------------------|-------------------------------|------|------------------|------------------|---------------------|------------------|------------------|------------------|----------------|----------------|----------------|----------------|------------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|--------------------------|
| 1   | 3:20:00.637               | −52:12:00.83                 | wf4  | 548.55           | 664.68           |                    | 22.58            | 21.41            |                  | 1.17             |                | 0.02           | 0.22           |                              | 0.03                       | 0.02                        |                              |                              | 0.00                      |
| 2   | 3:20:01.006               | −52:12:09.91                 | wf4  | 645.57           | 650.82           |                    | 22.03            | 20.93            |                  | 1.11             |                | 0.02           | 0.22           |                              | 0.02                       | 0.02                        |                              |                              | 0.00                      |
| 3   | 3:20:02.103               | −52:12:04.99                 | wf4  | 618.56           | 540.61           |                    | 23.47            | 22.35            |                  | 1.12             |                | 0.05           | 0.05           |                              | 0.07                       | 0.02                        |                              |                              | 0.00                      |
| 4   | 3:20:02.197               | −52:12:05.62                 | wf4  | 626.68           | 533.60           |                    | 23.18            | 22.08            |                  | 1.10             |                | 0.03           | 0.03           |                              | 0.04                       | 0.04                        |                              |                              | 0.00                      |
| 5   | 3:20:02.265               | −52:12:03.02                 | wf4  | 602.26           | 521.75           |                    | 21.84            | 20.55            |                  | 1.28             |                | 0.01           | 0.01           |                              | 0.02                       | 0.02                        |                              |                              | 0.00                      |
| 6   | 3:20:02.273               | −52:12:00.11                 | wf4  | 573.71           | 515.00           |                    | 22.47            | 21.31            |                  | 1.16             |                | 0.02           | 0.02           |                              | 0.03                       | 0.03                        |                              |                              | 0.00                      |
| 7   | 3:20:02.284               | −52:12:01.41                 | wf4  | 586.65           | 516.49           |                    | 23.77            | 23.84            |                  | −0.08            |                | 0.04           | 0.11           |                              | 0.12                       |                              |                              |                              |                          |
| 8   | 3:20:02.389               | −52:11:54.74                 | wf4  | 525.16           | 489.27           |                    | 24.51            | 23.92            |                  | 0.60             |                | 0.08           | 0.14           |                              | 0.16                       |                              |                              |                              |                          |
| 9   | 3:20:02.405               | −52:11:59.42                 | wf4  | 569.45           | 501.47           |                    | 23.47            | 22.47            |                  | 1.00             |                | 0.04           | 0.04           |                              | 0.05                       |                              |                              |                              |                          |
| 10  | 3:20:02.452               | −52:11:45.89                 | wf4  | 437.16           | 468.12           |                    | 23.48            | 22.53            |                  | 0.95             |                | 0.04           | 0.04           |                              | 0.06                       |                              |                              |                              |                          |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)
blue-plume stars appear to be a mix of hot main-sequence (MS) stars and post-MS blue supergiants (BSGs), based on where they lie in Figures 4(b) and (c). Second, only the turnoff stars of the hot MS are bright enough in $I_{814}$ to be unambiguously detected. The MS stars are bluer on average in $(U - V_{606})$ than the BSGs (see Figure 4(b)). We use this to refine our classification of blue-plume stars as either BSGs (more luminous and redder than the diagonal line in Figure 4(b)) or MS stars (less luminous and bluer than this line). Third, the red-plume stars are red supergiants (RSGs). They are nearly all undetected in $U_{300}$, but show a clear vertical plume structure in Figure 4(d). In Figures 4(b)–(d), the BSGs are circled and the RSGs are crossed. We note that the tip of the red giant branch (RGB) of an old stellar population is at an absolute magnitude of $M_I \approx -4.0$, which corresponds to an apparent magnitude of $m_I \approx 24.7$ for NGC 1311. This is much fainter than the magnitudes of the red-plume stars in Figure 4.

We show a selection of color–color diagrams in Figure 5, chosen to show both the BSGs and RSGs. In all cases, the BSGs are well isolated from the other detections, and the RSGs are mixed with red stars from neither plume. These are the faint red stars in Figure 4(d), and appear to be evolved stars from populations older than the bright RSG stars. As we have data in a somewhat unusual set of filters (even for HST observations), it seems prudent to compare our data to stellar population models before attempting any more detailed interpretation.

### 3.3. Isochrone Matching

We compare our stellar photometry to isochrones derived from the models of Girardi et al. (2002). In order to plot the isochrones with the photometry, we adopt the distance estimate for NGC 1311 of Tully et al. (2006), who quote $D = 5.45 \pm 0.08$ Mpc based on the magnitude of the tip of the RGB. There appear to be no metallicity measurements of NGC 1311 in the literature, although Kennicutt et al. (2008) report $[\text{N II}]/\text{H}$α $= 0.08$, consistent with a moderately low metallicity. For the adopted distance, we find that the isochrones with $Z = 0.004$ provide the best fit to the stellar photometry. The more metal-poor isochrones have main sequences that are substantially bluer than observed in all available colors. The isochrones more metal-rich than $Z = 0.008$ do not predict stars luminous enough in the UV or blue enough in colors including $F300W$ compared to the data. While crowding and/or binarity could artificially inflate the brightness of some fraction of our stars, our artificial star tests indicate that this is not a
Figure 4. CMDs for the detected stars in NGC 1311. The arrows in each plot show the foreground dereddening vectors. (a) $V_{606}$ vs. $(V_{606} - I_{814})$, (b) $UV_{300}$ vs. $(UV_{300} - V_{606})$, (c) $UV_{300}$ vs. $(UV_{300} - I_{814})$, and (d) $V_{606}$ vs. $(V_{606} - H_{160})$. The dotted boxes in panel (a) show the selection for the blue-plume and red-plume stars. We plot error bars for 1%–5% of the sample to avoid crowding. In panels (b)–(d), the circled points are BSG stars and the crossed points are RSG stars. The long-dashed lines show the 50% completeness limits. The solid line in panel (b) shows the separations between the BSGs and the hot MS stars.

Table 5
Artificial Star Photometric Accuracy

| Magnitude | $UV_{300}$ | $\sigma_{300}$ | $V_{606}$ | $\sigma_{606}$ | $I_{814}$ | $\sigma_{814}$ | $H_{160}$ | $\sigma_{160}$ |
|-----------|-----------|--------------|--------|------------|--------|-------------|--------|-------------|
| 17.0      | 0.028     | 0.230        | 0.008  | 0.014      |
| 17.5      | 0.021     | 0.203        | 0.014  | 0.030      |
| 18.0      | 0.004     | 0.075        | 0.021  | 0.037      |
| 18.5      | 0.005     | 0.094        | 0.002  | 0.012      | 0.031  | 0.053       |
| 19.0      | 0.000     | 0.025        | 0.001  | 0.010      | 0.002  | 0.013       | 0.060  | 0.115       |
| 19.5      | 0.011     | 0.036        | 0.001  | 0.011      | 0.003  | 0.016       | 0.088  | 0.157       |
| 20.0      | 0.015     | 0.043        | 0.001  | 0.013      | 0.005  | 0.022       | 0.120  | 0.202       |
| 20.5      | 0.021     | 0.061        | 0.002  | 0.016      | 0.007  | 0.026       | 0.195  | 0.295       |
| 21.0      | 0.027     | 0.081        | 0.003  | 0.017      | 0.010  | 0.034       | 0.268  | 0.426       |
| 21.5      | 0.024     | 0.109        | 0.004  | 0.022      | 0.013  | 0.050       | 0.313  | 0.570       |
| 22.0      | 0.009     | 0.144        | 0.008  | 0.033      | 0.022  | 0.061       |
| 22.5      | 0.112     | 0.238        | 0.007  | 0.043      | 0.028  | 0.091       |
| 23.0      | 0.358     | 0.463        | 0.011  | 0.066      | 0.044  | 0.144       |
| 23.5      | 0.899     | 0.996        | 0.013  | 0.097      | 0.043  | 0.177       |
| 24.0      | 0.025     | 0.120        | 0.054  | 0.216      |
| 24.5      | 0.023     | 0.169        | 0.391  | 0.508      |
| 25.0      | 0.010     | 0.217        |
| 25.5      | 0.196     | 0.352        |
| 26.0      | 0.728     | 0.871        |
| 26.5      | 1.699     | 1.842        |
| 27.0      | 2.524     | 2.645        |

significant problem at the bright end of our photometry. We adopt a metallicity of $Z = 0.004$ below.

In Figures 6 and 7, we show the suite of CMDs and color–color diagrams from Figures 4 and 5, with the Girardi et al. (2002) $Z = 0.004$ isochrones overlayed. The most luminous stars in NGC 1311 have absolute visual magnitudes of about $-8.5$. Based on the isochrone comparison, the CMDs show a mix of young ($\lesssim 10$ Myr old) MS stars, and supergiants with ages ranging from $\sim 10$ Myr up to $\sim 1$ Gyr. There is some evidence of a small population of stars younger than 10 Myr (see Figure 6(b)). The isochrones are broadly consistent with the stellar distribution in the color–color diagrams, with a few exceptions. There are stars, including a few of the BSGs, that appear anomalously red in colors involving $H_{160}$. Inspection of the images shows that the stars in question typically have faint companions visible in the F606W and F814W images. At the poorer sampling of the F160W image, these companions are blended with the brighter stars. If the companion stars are red, this will create exactly the offset we observe in the color–color plots. There are a few stars, not selected as supergiants, that have colors that are very red in colors involving F606W and

6 Our F606W and F814W images are deep enough to reveal only the tip of the old RGB that is clearly revealed in the ACS data discussed by Tully et al. (2006). As we are concerned with the young stellar population, this is not a central issue for our study.
redder filters. These stars are too faint in $V_{606}$, given their magnitudes in $I_{814}$ and $H_{160}$, to match the isochrone models. We speculate that these stars may be dust enshrouded asymptotic giant branch stars. There is also the possibility that a few objects are unresolved background extremely red objects (e.g., Wilson et al. 2007).

4. DISCUSSION

The isochrone matching reinforces the qualitative impressions from the CMDs and color–color plots. The blue-plume stars are a mix of hot MS stars with ages of $\lesssim 10$ Myr and BSGs with ages from $\sim 10$ up to $\sim 40$ Myr. The red-plume stars are RSGs with ages from $\sim 10$ up to $\sim 100$ Myr. The hot MS stars are generally well-matched by the same 10 Myr isochrone that describes the youngest of the BSGs. The distribution of MS and BSG stars in Figures 6(a)–(c), as well as the $H\alpha$ emission reported by Kennicutt et al. (2008), are evidence for star formation in the last $\sim 10$ Myr, but at a rate much lower than 10 Myr ago. We thus see evidence for a burst of star formation about 10 Myr ago superposed on what had been lower level, but ongoing star formation over (at least) the previous 100 Myr or so.

4.1. Blue- and Red-Plume Stars

The use of the ratio of blue to red supergiants (hereafter B/R ratio) as an astrophysical diagnostic of stellar populations was first suggested by van den Bergh (1968). The B/R ratio turns out to depend on (at least) the metallicity and age of a stellar population. Maeder & Meynet (2001) and Eggenberger et al. (2002) provide recent work on the relevant theory, while Dohm-Palmer & Skillman (2002) and Úbeda et al. (2007) present recent observational results in the context of nearby low-luminosity star-forming galaxies.

The boxes in Figure 4(a) enclose 280 blue-plume and 190 red-plume stars (295 and 200, after correcting for incompleteness). However, as noted in Section 3.2, not all the blue-plume stars identified in Figure 4(a) are BSGs. Also, as pointed out by Dohm-Palmer & Skillman (2002), the blue and red supergiant plumes in the CMDs of nearby galaxies will, in general, be due to stars of a range of ages. As, even for a fixed metallicity, the B/R ratio is a function of age, some care is required to choose fair samples of stars to evaluate the B/R ratio. We have small samples to work with, so we choose to define three age-based samples, using the isochrones in Figure 6(a), with rough ages of 10 Myr, 18 Myr, and 32 Myr. It is well known that models of RSGs do not produce stars as red as observed (see Úbeda et al. 2007, and references therein). Thus, we include, as RSGs of a given age, those stars that lie to the red of the isochrone red loops at a given luminosity. In Table 6, we show the resulting age-based samples of BSGs and RSGs, and the B/R ratios for these samples. The quoted uncertainties in Table 6 are from Poisson statistics. At a given age, we have somewhat smaller B/R ratios than Dohm-Palmer & Skillman (2002) found for Sextans A. This is consistent with a higher metallicity for NGC 1311 than for Sextans A. The Sextans A metallicity, from both $H\beta$ region spectroscopy (Skillman et al. 1989) and CMD fitting (Dohm-Palmer & Skillman 2002), is $Z \approx 0.001$, compared to our adopted metallicity for NGC 1311 of $Z = 0.004$. This conclusion is reinforced by the $[N\text{II}]/H\alpha$ ratios of the two galaxies reported by Kennicutt et al. (2008).

4.2. Distribution of Recent Star Formation

In addition to the BSG and RSG samples selected above, we define a sample of hot MS stars by taking all stars fainter than $UV_{300} = 20.7$ mag, and blueward of a line extending from ($-2.6, 20.7$) to ($0, 22.8$) in Figure 4(b). We show the distribution...
Figure 6. CMDs of Figure 4 with isochrones from Girardi et al. (2002). The isochrones have $Z = 0.004$, and cover a range in age from 4 Myr (blue) to 6 Gyr (red). The solid lines show the 10 Myr, 100 Myr, and 1 Gyr isochrones. The dotted lines are younger, intervening, and older isochrones, sampled every 0.25 dex in age (symbols as in Figure 4).

Table 6

| Age (Myr) | BSG Uncorrected | RSG Uncorrected | B/R Ratio Uncorrected | BSG Corrected | RSG Corrected | B/R Ratio Corrected |
|-----------|-----------------|-----------------|-----------------------|---------------|---------------|----------------------|
| 10        | 13 ± 3.6        | 3 ± 1.7         | 4.3 ± 2.7             | 13.5 ± 3.6    | 3.1 ± 1.7     | 4.4 ± 2.7             |
| 18        | 16 ± 4.0        | 24 ± 4.9        | 0.67 ± 0.22           | 16.7 ± 4.0    | 25.0 ± 4.9    | 0.70 ± 0.22           |
| 32        | 53 ± 7.3        | 53 ± 7.3        | 1.00 ± 0.19           | 55.2 ± 7.3    | 55.2 ± 7.3    | 1.00 ± 0.19           |

of all three samples (MS, BSG, RSG) on the F300WWF3+WF4 image in Figure 8. We note that there are a handful of sources that are not assigned to any of the three groups. The brightest of these are the star clusters discussed in Eskridge et al. (2008). The fainter sources are only detected in $UV_{300}$. These are likely to be MS stars, but as we do not have colors for them, we do not classify them as such. There are two regions with strong concentrations of MS and BSG stars. The boxes in Figure 1(a) enclose these two regions. In Figure 9, we show CMDs of the stars in the boxes and in the rest of the galaxy. Nearly half the recent star formation in NGC 1311 has occurred in these two small regions, with the remainder broadly distributed throughout the system. The total area of the two regions is about 0.15 kpc$^2$ for our adopted distance, or about 2% of the surface area of NGC 1311. These regions are also the locations of the strong H$\alpha$ emission shown in Meurer et al. (2006).

The regions of enhanced recent star formation are about 10$''$ across. This corresponds to roughly 200 pc for our adopted distance. Velocity-dispersion measurements in late-type galaxies, for either stars or gas, are sparse but have characteristic values of about 10–20 km s$^{-1}$ (e.g., Hunter et al. 2001, 2002, 2005). If we assume that the velocity dispersion of the stars in the concentrations is similar to this, the stars will travel roughly 100–200 pc in 10 Myr. Thus, the sizes of the concentrations of young stars are consistent with the ages implied by the CMDs. We can also compare these regions to Galactic OB associations. OB associations are unbound groups of young stars that appear to be dispersing with internal velocity dispersions of $\approx 5$ km s$^{-1}$ (e.g., Blaauw 1964; Hills 1980; Bobylev & Bajkova 2007). This gives a slightly longer lifetime, but one that is still in the range of tens of Myr.

4.3. Star Formation History

The distribution of star cluster ages in NGC 1311 is consistent with a bursting mode of cluster formation, with active episodes
of age \( \sim 10 \) Myr, \( \sim 100 \) Myr, and \( \gtrsim 1 \) Gyr (Eskridge et al. 2008). The resolved stars tell us a complimentary, but different story: they do not show any compelling evidence for substantial periods of quiescence in the last \( \sim 100 \) Myr. Our CMDs show a clear population of stars with ages \( \sim 10 \) Myr. These are the MS and BSG stars seen in all panels of Figure 6. There is evidence of low-level ongoing star formation over the last 10 Myr (see Figure 6(b)). The distribution of BSGs and RSGs in the CMDs tell us that there was ongoing star formation in NGC 1311 from \( \sim 10 \) Myr ago back to at least \( \sim 100 \) Myr ago. Although we are mainly concerned with the young stellar populations, we note that Figure 6(d) and the work of Tully et al. (2006) argue that star formation occurred in a more or less steady fashion back to ages of at least \( \sim 1 \) Gyr.

We can make a somewhat more quantitative assessment of the recent star formation history from the luminosity function (LF) of the core helium burning stars, as was first pointed out by Dohm-Palmer et al. (1997). In Figure 10, we show the differential LFs of the BSG and RSG stars, with age points from the models of Marigo et al. (2008). To convert the LFs into a star formation history, we need to specify an initial mass function (IMF) and a stellar evolution model. We use the Salpeter IMF (Salpeter 1955) and the Padua stellar evolution models (Marigo et al. 2008), and apply them following the precepts of Dohm-Palmer et al. (1997). Figure 11 shows the resulting star formation history in the age range 10–40 Myr from the BSGs. The error bars in Figure 11 represent statistical uncertainties from the star counts only. There are additional systematic
uncertainties due to the adopted IMF and stellar evolution model. These will affect the absolute normalization of the star formation history, but should not substantially affect either its shape or its timescale. The most luminous BSGs have ages of \(\sim 10\) Myr. At ages above \(\sim 40\) Myr, it becomes impossible to isolate the BSGs on the CMDs. Over the time period we can address, the rate of star formation appears to have been rising steadily, ending in a strong enhancement \(\sim 10\) Myr ago that corresponds to the most recent epoch of cluster formation.

There are no BSGs more luminous than \(M_{V606} = -8.5\). This indicates that star formation did not continue at the rate seen \(\sim 10\) Myr ago. In principle, this is quantifiable by studying the MS LF. The upper MS stars are most easily isolated in the \(U V_{300}\) versus \((U V_{300} - V_{606})\) CMD (see Figures 4(b) and 6(b)). The 50% completeness limit is at \(V_{606} \approx 22.1\) mag, corresponding to an absolute magnitude of \(M_{UV_{300}} \approx -6.6\). This means our data only probe the upper \(\sim 1\) mag of the MS LF. We applied the iterative technique of Dohm-Palmer et al. (1997) to the completeness-corrected MS LF of NGC 1311, again assuming a Salpeter IMF and the Padua models. The result is that the upper MS stars provide evidence for star formation from 2 to 2.5 Myr ago. The absolute star formation rate has large statistical uncertainty due to the small number of stars and the large completeness corrections. But there has clearly been residual ongoing star formation in NGC 1311 since the enhancement in star formation \(\sim 10\) Myr ago.

We can extend the star formation history back to \(\sim 100\) Myr by taking advantage of the RSGs. We caution the reader that theoretical modeling of the evolution of RSGs is on a less firm footing than that of BSGs (Laçon et al. 2007). Our resulting star formation history will therefore be subject to additional systematic uncertainty for ages larger than 40 Myr. However, we proceed, again using a Salpeter IMF and the Padua models. The resulting star formation history is shown in logarithmic form in Figure 12. Over the last \(\sim 100\) Myr, the star formation rate in NGC 1311 appears to have been gradually increasing, peaking with the enhancement \(\sim 10\) Myr ago. We see no evidence for any gap in star formation over the last \(\sim 100\) Myr. These data are more consistent with a star formation history described as gasping or breathing (e.g., Marconi et al. 1995; Skillman 2005; Stinson et al. 2007) than bursting.

In Eskridge et al. (2008), we identified a small population of star clusters in NGC 1311. Eight of these clusters have sufficient multiwavelength photometry to use for age estimation. These ages break into three groups. Two clusters have ages of \(\lesssim 10\) Myr. These clusters would appear to be associated with the enhanced episode of star formation \(\sim 10\) Myr ago that is revealed by the BSGs (see Figure 11). We note that the total mass in stars formed...
in the 10 Myr enhancement is about an order of magnitude larger than the mass estimated by Eskridge et al. (2008) for the two young clusters.

There are no clusters with ages in the interval from 10 to 50 Myr. The BSGs show that there was low-level ongoing star formation throughout this interval, but no bound clusters survive from it. As we note in Section 4.2, the BSGs are concentrated in two regions with properties similar to Galactic OB associations. That is, the stars in that age range are spatially clumped, but they do not inhabit gravitationally bound clusters.

Four clusters have ages between 50 Myr and 130 Myr. The RSGs show evidence for a gradually increasing star formation rate toward the younger/more recent part of this range. How this relates to the cluster formation in this epoch may be discernable by a more extensive analysis of the HST Advanced Camera for Surveys data than was reported by Tully et al. (2006). However, we note that the total mass in intermediate-age clusters (Eskridge et al. 2008) is roughly equal to the total mass in intermediate-age field stars based on the RSG LF. Thus, the star formation of ~100 Myr ago was efficient at producing clusters dense enough to remain bound over ~100 Myr timescales, whereas the 10 Myr enhancement appears to have produced mainly unbound stellar associations.

4.4. The Luminosity–Metallicity Relation

Fits to isochrones indicate a metallicity of $Z \approx 0.004 ([Z/H] \approx -0.7)$, consistent with $[N \text{ II}]/H\alpha = 0.08$ (Kennicutt et al. 2008). Given its absolute magnitude (see Table 1), this places NGC 1311 in the midst of the magnitude–metallicity relation for late-type dwarf galaxies (e.g., Mateo 1998). We show this in Figure 13, where we plot $B$-band absolute magnitudes and nebular oxygen abundances for star-forming dwarf galaxies from a number of recent studies.
Figure 12. Star formation history from 10 Myr to 100 Myr ago from the BSG and RSG stars. The star formation rate is shown in logarithmic form. The solid and dashed histograms show the star formation history from the BSGs and RSGs, respectively. The error bars are statistical errors from the observed counts.

Figure 13. Absolute B-band magnitudes vs. $12 + \log(O/H)$ for late-type dwarf galaxies from several recent studies: solid circles, Lee et al. (2007); solid squares, Lee et al. (2003a); solid triangles, Lee et al. (2003b); open triangle (WLM), Lee et al. (2005); open square (NGC 6822), Lee et al. (2005); open circle (NGC 1705), Lee & Skillman (2004); crosses, Skillman et al. (2003). The large diamond shows our estimate for NGC 1311.

We detect hot MS stars in the UV and optical images, providing strong evidence for star formation as recently as $\sim 2$ Myr ago. We also detect BSG and RSG stars that provide evidence of ongoing star formation over the last $\sim 100$ Myr. Our NIR data reveal populations of stars as old as $\gtrsim 1$ Gyr, in agreement with the work of Tully et al. (2006). The field stars of NGC 1311 show a less burst-like age distribution than do the star clusters in NGC 1311 (Eskridge et al. 2008). About half of the recent star formation, as traced by the MS and BSG stars, is confined to two regions about 200 pc across in the bright central part of the system. Assuming a velocity dispersion for the stars that is typical of Galactic OB associations, the crossing time is on the order of the age of 10 Myr determined from the CMDs. The metallicity of $Z \approx 0.004$ that follows from the isochrone fits and the B/R ratio places NGC 1311 in the midst of the metallicity–luminosity relation for low-luminosity late-type galaxies.

5. SUMMARY AND CONCLUSIONS

NGC 1311 is a nearby ($D \approx 5.5$ Mpc) late-type (SBm) galaxy. We have analyzed stellar photometry from HST images of this galaxy covering a wavelength range from 0.3 to 1.6 $\mu$m. (Skillman et al. 2003; Lee et al. 2003a, 2003b, 2005, 2006, 2007; Lee & Skillman 2004). To place NGC 1311 on the figure, we convert the linear metallicity ($Z = 0.004$) to logarithmic notation, assuming $Z_\odot = 0.019$. This gives $[Z/H] = -0.68$. If we further assume that $[Z/O] = 0$ for NGC 1311, and take $12 + \log(O/H)_\odot = 8.93$ from Anders & Grevesse (1989), this gives us an estimate of $12 + \log(O/H) \approx 8.25$ for NGC 1311. This is shown in Figure 10 as a large diamond. As noted in Section 4.1, our metallicity estimate is also consistent with the observed B/R ratios for supergiants as sorted by age.
Our results for NGC 1311 are consistent with those found for the general population of late-type, low-luminosity galaxies (e.g., Marconi et al. 1995; Mateo 1998; Hunter et al. 2001; Young et al. 2003; Bernard et al. 2007; Stinson et al. 2007; Saviane et al. 2008; Sharina et al. 2008; Weisz et al. 2008). The arising consensus is that such galaxies form stars over their entire histories. The rate of star formation may change with time, but only rarely does it cease entirely. The long-term star-forming histories of low-luminosity galaxies are best studied with deep long-wavelength optical (RI) or NIR (JHK) images. Our UV and optical data allow us to explore the star-forming history of NGC 1311 over the last ~100 Myr.

Our next step is a study of the unresolved light of NGC 1311 with our combined WFC2/NICMOS HST data. As we have observations in four wavelengths from 3000 Å to 1.6 μm, we will sample stellar populations from ages of ~10 Myr to >10 Gyr. Nearby star-forming galaxies are known to have unresolved UV light (e.g., Chandar et al. 2005) at HST resolution. The stellar photometry we present in this paper provides information on individual MS stars as late as early B-type stars. Late B-type and A-type stars will contribute significant diffuse UV light that traces the distribution of stars of ~100 Myr ages. The ancient stellar populations, dominating the NIR light, appear ubiquitous even in very late type galaxies (e.g., Baade 1958; Taylor et al. 2005). The combination of our cluster and stellar photometry with an analysis of the unresolved light should give us a clearer picture of the star formation history in this system, and a fuller understanding of the process of star formation in low-luminosity late-type galaxies in general.

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Facility: HST

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