THE ACS NEARBY GALAXY SURVEY TREASURY. VII. THE NGC 4214 STARBURST AND THE EFFECTS OF STAR FORMATION HISTORY ON DWARF MORPHOLOGY

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**ABSTRACT**

We present deep Hubble Space Telescope WFPC2 optical observations obtained as part of the ACS Nearby Galaxy Survey Treasury as well as early release Wide Field Camera 3 ultraviolet and infrared observations of the nearby dwarf starbursting galaxy NGC 4214. Our data provide a detailed example of how covering such a broad range in wavelength provides a powerful tool for constraining the physical properties of stellar populations. The deepest data reach the ancient red clump at \(M_{\text{F814W}} \sim -0.2\). All of the optical data reach the main-sequence turnoff for stars younger than \(\sim 300\) Myr and the blue He-burning sequence for stars younger than \(500\) Myr. The full color–magnitude diagram (CMD) fitting analysis shows that all three fields in our data set are consistent with \(\sim 75\%\) of the stellar mass being older than \(8\) Gyr, in spite of showing a wide range in star formation rates at present. Thus, our results suggest that the scale length of NGC 4214 has remained relatively constant for many gigayears. As previously noted by others, we also find the galaxy has recently ramped up production consistent with its bright UV luminosity and its population of UV-bright massive stars. In the central field we find UV point sources with \(F336W\) magnitudes as bright as \(-9.9\). These are as bright as stars with masses of at least \(52–56 M_{\odot}\) and ages near \(4\) Myr in stellar evolution models. Assuming a standard initial mass function, our CMD is well fitted by an increase in star formation rate beginning \(100\) Myr ago. The stellar populations of this late-type dwarf are compared with those of NGC 404, an early-type dwarf that is also the most massive galaxy in its local environment. The late-type dwarf appears to have a similar high fraction of ancient stars, suggesting that these dominant galaxies may form at early epochs even if they have low total mass and very different present-day morphologies.

**Key words:** galaxies: evolution – galaxies: individual (NGC-4214) – galaxies: spiral – galaxies: stellar content

**Online-only material:** color figures

1. INTRODUCTION

Irregular galaxies are the dominant type of star-forming galaxies by number. Despite their typically isolated environments and relatively low mass, the star formation histories (SFHs) of irregular galaxies are surprisingly complex and varied. In the context of hierarchical structure formation, the formation epoch of these galaxies is expected to be younger than that of more massive galaxies, a phenomenon referred to as cosmic downsizing. Deep resolved stellar photometry allows us to measure their formation epoch and to examine their recent SFHs in detail.

Historically, early-type dwarfs were thought to be dominated by ancient populations (Baade & Gaposchkin 1963; Zinn 1980), while dwarf irregular galaxies (dIrrs) have been considered to be formed by ancient populations (Baade & Gaposchkin 1963; Zinn 1980), and the recent formation episodes may be the only difference between these classes of dwarf galaxies and that such recent episodes of star formation actually contribute very little to the total stellar mass of the systems. Therefore, the difference between these distinct morphological types may be due to only a very small fraction of the stellar mass. To further investigate the possibility that the vast majority of the stellar mass in dIrrs can be as old as the stellar mass of early-type dwarfs and that the star formation events witnessed in dIrrs are episodic, we focus our attention on the nearby galaxy NGC 4214.

NGC 4214 is classified as an irregular galaxy (IAB(s)m; de Vaucouleurs et al. 1991) with a mass of \(\sim 1.5 \times 10^{8} M_{\odot}\) (Karachentsev et al. 2004), similar to the Large Magellanic Cloud. It is one of the nearest examples of a starburst, and was the host of a Type I supernova (Wellmann 1955) and a recent nova (Humphreys et al. 2010). It therefore has been studied in detail, especially at UV and near-IR wavelengths that probe the young stellar populations. For example, Fanelli et al. (1997) were able to make use of far-UV imaging from the Ultraviolet Imaging

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Telescope and ground-based $J$ band to decompose the galaxy into a centrally concentrated, intense star-forming component and an extended smooth disk. They suggest the two-component structure is the result of a recent merger.

The bright resolved stellar populations have also been characterized. A dominant red giant branch (RGB) was detected, and a large metallicity spread was measured by Drozdovsky et al. (2002) using WFPC2 and NICMOS photometry. Úbeda et al. (2007a, 2007b) used imaging from the Hubble Space Telescope (HST)/WFPC2 and HST/Space Telescope Imaging Spectrograph to suggest that the stellar initial mass function (IMF) appears to be steeper than that of Salpeter (1955) at high masses (>20 $M_\odot$), even though the galaxy's metallicity is similar to that of the Small Magellanic Cloud. However, it is unclear how this slope is affected by fluctuations in the star formation rate (SFR).

We further examine the stellar populations of NGC 4214 using deeper data than previous studies. The new data include two HST/WFPC2 fields of the outer disk and one Wide Field Camera 3 (WFPC3) field of the inner regions. Through detailed stellar evolution model fitting, we measure the SFH of these regions and look for differences between quiescent and intense star-forming regions. Section 2 describes our data set and photometry. Section 3 presents the results of our model fitting procedure. Section 4 discusses the results of the measurements in the context of galaxy morphology and environment, and Section 5 summarizes our conclusions. We assume $(m - M)_0 = 3.03$ Mpc (Dalcanton et al. 2009) for conversions of angular measurements to physical distances and assume an inclination of $38^\circ$ (Karachentsev et al. 2004) for surface density measurements. We adopt a five-year Wilkinson Microwave Anisotropy Probe cosmology (Dunkley et al. 2009) for all conversions between time and redshift.

## 2. DATA

As part of the ACS Nearby Galaxy Survey Treasury (ANGST) program after the failure of the Advanced Camera for Surveys (ACS), from 2007 December 4 to 23 we performed deep WFPC2 observations for a field in the NGC 4214 disk located at R.A. (2000) = 183.847375 (12:15:23.4), decl. (2000) = 36.362333 (+36:21:44) with a rotation angle $PA_{V3} = 119.9$ deg (GO-10915). To improve our radial coverage to be closer to the goal of the original ANGST program, from 2009 February 23 to 26 we performed shallower supplemental observations for a field located at R.A. (2000) = 183.878103 (12:15:30.7), decl. (2000) = 36.356808 (+36:21:24.5) with a rotation angle $PA_{V3} = 51.0$ (GO-11986). At the same time, WFPC3/IR and WFPC3/UVIS imaging of the central area of the galaxy, proposed by the Scientific Oversight Committee, were released. Both fields were observed from 2009 December 22 to 23 located at R.A. (2000) = 183.913333 (12:15:39.2), decl. (2000) = 36.326944 (+36:19:37.0) with a rotation angle $PA_{V3} = 120.0$ (GO-11360, PI: O’Connell). Figure 1 shows outlines of the fields’ locations. Our field locations were chosen to maximize the number of disk stars and avoid crowding.

In the deep field, we obtained six full-orbit exposures with the WFPC2 through the F606W (wide V) filter and 12 full-orbit exposures through the F814W (I equivalent) filter. These data totaled 39,000 s and 75,400 s of exposure time in F606W and F814W, respectively. In the other WFPC2 field, we obtained four orbits through F606W totaling 9600 s, and seven orbits through F814W totaling 17,800 s. The WFPC3/IR data contained 1198 s and 2398 s of exposure in F110W and F160W, respectively. The WFC3/UVIS data contained 1683 s, 1540 s, and 1339 s in F336W, F438W, and F814W, respectively. All WFPC2 images were calibrated in the HST pipeline with CALWFP2 using OPUS version 2006.6a for the 2007 data and 2008.5c for the 2009 data. All WFC3 images were calibrated in the HST pipeline with CALWF3 version 2.0.

### 2.1. Photometry

All of the data were processed through the ANGST data analysis pipeline (Dalcanton et al. 2009) updated to include WFC3/UVIS and IR data (J.J. Dalcanton et al. 2011, in preparation). As a brief summary, the photometry was measured simultaneously for all of the objects in the uncombined images using the software packages HSTPHOT (for WFPC2) and DOLPHOT 1.2 (Dolphin 2000, 2009) including the WFC3 module. These packages are optimized for measuring the photometry of stars on HST images using the well-characterized and stable point-spread function (PSF) calculated with Tiny Tim. The software fits the PSF to all of the stars in each individual frame to find PSF magnitudes. It then determines and applies the aperture correction for each image using the most isolated stars, corrects for the charge transfer efficiency of the WFPC2 detector, combines the results from the individual exposures, and converts the measured count rates to the VEGAMag system.

Our photometric error and completeness were then assessed by running at least 10$^3$ artificial star tests for each field, in which a star of known color and magnitude was placed into the images and the photometry rerun to determine if the star was recovered and, if so, the difference between the input and output magnitude.

The photometry output was then filtered to only allow objects classified as stars with signal-to-noise ratios >4 in both filters. The list was further culled using sharpness ($|F606W_{\text{sharp}} - F814W_{\text{sharp}}| < 0.27$ for WFPC2, $|F336W_{\text{sharp}} - F438W_{\text{sharp}}| < 0.27$ for UVIS, and $|F110W_{\text{sharp}} - F160W_{\text{sharp}}| < 0.35$ for IR) and crowding ($F606W_{\text{crowd}} + F814W_{\text{crowd}} < 0.7$ for WFPC2, $F336W_{\text{crowd}} + F438W_{\text{crowd}} < 0.7$ for UVIS, and $F110W_{\text{crowd}} + F160W_{\text{crowd}} < 0.48$ for IR). The sharpness parameter returns zero if a star is perfectly fit, negative if it is broader than a typical star, and positive if it is sharper (Dolphin 2000). The crowding parameter gives the difference between the magnitude of a star measured before and after subtracting the neighboring stars in the image. When this value is large, it suggests that the star’s photometry was significantly affected by crowding, and we therefore exclude it from our catalog. The values for the sharpness and crowding cuts for WFPC2 were the standard used by the ANGST program. The cuts for WFC3 were chosen by looking at color–magnitude diagrams (CMDs) resulting from different possibilities and choosing values that produced clean CMD features and a low number of contaminants falling outside of any known feature. We note that our tests of different cuts showed that the choices of cuts have little impact on our final SFH measurements outside of the most recent time bin (<10 Myr), most likely due to the significant clustering of the very youngest stars. Our final optical star catalogs contained 16806, 28088, 138350, and stars for the outer (WFPC2 N), bridge (WFC3 NW), and central (UVIS) fields, respectively.

Our final UV catalog for the central field contained 77,656 stars and our final IR catalog for the central field contained

6. [http://www.stsci.edu/software/tinytim/](http://www.stsci.edu/software/tinytim/)

7. 2008 July formulae [http://purcell.as.arizona.edu/wfpc2_calib/2008_07_19.html](http://purcell.as.arizona.edu/wfpc2_calib/2008_07_19.html)

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Figure 1. Locations of our NGC 4214 fields are shown on a three-color image using Sloan Digital Sky Survey (SDSS) $u'$ (blue), $g'$ (green), and $i'$ (red) images. North is up. East is left. The small central field is WFC3/IR. The larger central field is WFC3/UVIS. The outer fields are WFPC2, with the westernmost being the deepest. (A color version of this figure is available in the online journal.)

38,884 stars. In the end, our analysis of the optical ($F_{438}W$ and $F_{814}W$) photometry from UVIS yielded results that were consistent with those of the UV ($F_{336}W$ and $F_{438}W$) photometry from UVIS. Since no additional insight was gained from the optical photometry, we will not discuss it further but include the SFH and limiting magnitudes for reference. Any statement made about the UV photometry from UVIS was confirmed with the optical photometry from UVIS. The final CMDs are shown in Figure 2.

2.2. Field Division

While all the WFPC2 imaging of the outer portions of the disk provided high-quality photometry going much fainter than the tip of the RGB (and even fainter than the red clump in the deep field), the central WFC3 fields were not as consistent. The UVIS images proved to have similar completeness limits throughout the field, but the IR images were clearly overcrowded near the galaxy center. This strong differential crowding in the IR data made analysis of the full IR field dubious. We therefore separated the innermost portion of the central field into two spatial components, following the isophotes of the galaxy. Our division ellipse and the galaxy isophotes in the $F_{110}W$ image are shown in Figure 3.

3. CMD FITTING AND TEMPORAL RESOLUTION

We measured the SFR and metallicity as a function of stellar age using the software package MATCH (Dolphin 2002) to fit the observed CMDs. We adopted magnitude cuts set to the limits provided in Table 1, and then fitted the stellar evolution models of Girardi et al. (2002; with updates in Marigo et al. 2008 and Girardi et al. 2008), convolved with our photometric error and completeness statistics and populated with a Salpeter (1955) IMF. The choices of software and models used for the ANGST project are discussed in detail in Williams et al. (2009b). Briefly, comparisons of results when fitting CMDs using different models and fitting software have shown that
the results are consistent within the estimated uncertainties; furthermore, our choice of models provides the largest range of ages and metallicities publicly available.

We first fitted the data assuming a single foreground reddening of $A_V = 0.07$ and a distance of $m - M_0 = 27.41$, which were obtained from the ANGST survey (Dalcanton et al. 2009) and the Schlegel et al. (1998) galactic dust maps. The best fit provides the relative contribution of stars of each age and metallicity in each field. For the shallowest data, the IR and optical data for the innermost region, we limited the number of free parameters by imposing an “increasing metallicity” constraint on the fit, whereby the metallicity of the population was not allowed to decrease with time (within the measured errors). These fits were turned into SFHs of SFR and metallicity as a function of time.

To assess the uncertainties of our fits, we then ran Monte Carlo fitting tests. These tests assessed two types of errors: random errors due to Poisson sampling and errors in photometry, and systematic errors due to deficiencies in the stellar evolution models as well as any offset in distance, reddening, and/or zero-points. The Poisson errors were accounted for by resampling the convolved best-fit model 100 times. Then, when fitting each of these realizations, the systematic errors were accounted for by introducing small random shifts in the bolometric magnitudes and effective temperatures of the models. These shifts were introduced at the level of the differences between models in the literature, and therefore served as proxies for the effects of our choice of stellar evolution models.

Our final uncertainties were calculated as 68% confidence intervals of the results of all of our Monte Carlo test fits. These
Figure 3. WFC3 image of the central 2′ × 2′ of NGC 4214 shown in a three-color image using WFC3 F438W (blue), F110W (green), and F160W (red) images. North is up. East is left. Isophotal contours are shown in green. Our field division ellipse is shown in white. The inner region is much more crowded and dusty than the outer region, making CMD fitting more reliable when the two regions are modeled separately.

(A color version of this figure is available in the online journal.)

Table 1

| Region       | F336W50a | F438W50b | F606W50c | F814W50d | F110W50e | F160W50f | GCDg |
|--------------|----------|----------|----------|----------|----------|----------|------|
| UV INNER     | 26.0     | 27.1     | ...      | ...      | ...      | ...      | 0.34 |
| UV OUTER     | 26.1     | 27.2     | ...      | ...      | ...      | ...      | 1.15 |
| IR INNER     | ...      | ...      | ...      | 23.5     | 22.7     | ...      | 0.52 |
| IR OUTER     | ...      | ...      | ...      | 24.0     | 23.2     | ...      | 0.99 |
| BI INNER     | ...      | 26.9     | 26.0     | ...      | ...      | ...      | 0.48 |
| BI OUTER     | ...      | 27.1     | 26.2     | ...      | ...      | ...      | 1.10 |
| WFPC2 N      | ...      | ...      | 26.7     | 26.1     | ...      | ...      | 2.27 |
| WFPC2 NW     | ...      | ...      | 27.9     | 27.1     | ...      | ...      | 3.17 |

Notes.

a The 50% completeness limit of the F336W data.
b The 50% completeness limit of the F438W data.
c The 50% completeness limit of the F606W data.
d The 50% completeness limit of the F814W data.
e The 50% completeness limit of the F110W data.
f The 50% completeness limit of the F160W data.
g The median deprojected galactocentric distance of the stars in the region (in kpc).

We can also assess the degree of systematic errors using plots of residuals between the observed CMD and the model

total uncertainties were used as the error bars in all subsequent plots and analysis.
Figure 4. Observed (upper left), best-fit model (upper right), difference (lower left), and difference normalized by uncertainty (lower right) CMDs of our fit to the UVIS data of the inner region of NGC 4214. Scale bars are shown to the right of each plot. The fit is generally good over the entire CMD assuming foreground extinction, but also shows a modest amount of internal extinction (cf. Section 4.2), which causes the slight excess in the data redward of the model main sequence. (A color version of this figure is available in the online journal.)

fit. An example of the residuals of our fits is shown in Figure 4. Our fits assume the galactic foreground extinction over the field. Therefore, the low-level residuals over the entire CMD for these fits suggest that our photometry is dominated by stars in front of any significant internal dust layer in the NGC 4214 disk, with a modest amount of internal extinction (cf. Section 4.2) causing the slight excess in the data redward of the model main sequence. These fits show that the MS luminosity profile interpreted by Ubeda et al. (2007a, 2007b) as suggesting variations in the IMF is also consistent with a standard IMF with a varying SFH; thus, IMF variations and SFH are somewhat degenerate in such a complex region. Our uncertainties come from measurements assuming a constant IMF. Therefore, our uncertainties would increase if variations in the IMF were allowed.

We used a very fine grid of model stellar isochrones (0.05 dex in age and 0.1 dex in [Fe/H]) to provide the best possible fit to our data. Because the grid is very fine, pushing star formation between adjacent time bins has little effect on the quality of the resulting fit. The degree to which this degeneracy is true depends on the quality of the data being fitted, which is characterized by our Monte Carlo tests.

The uncertainties in the cumulative age distribution cannot be improved by further binning of the data in time. Therefore, we plot the full time resolution of our fit to the cumulative age distribution, showing the uncertainties from our Monte Carlo tests, which include the effects of pushing star formation between adjacent time bins.

On the other hand, within a given time bin, the uncertainty on the measured mean SFR is related to the sensitivity of the CMD fit to stars in that age bin. As the size of the bin increases, more locations of the CMD will be affected by the bin. Thus, increasing the bin size increases the sensitivity of the CMD fit to that time bin, thereby reducing the uncertainty on the mean rate within that time bin. It is therefore possible to reduce the uncertainties on the measured SFR by increasing the length of the time bins.

To determine optimal time bins for our differential SFH, we apply the uncertainties in our cumulative age distribution, as determined from our Monte Carlo tests. Specifically, we define bins for which the cumulative fraction of stars increased with statistical significance. The bins are defined so that at each bin boundary, the 1σ upper limit of the cumulative fraction of stars formed in the older bin must be less than the 1σ lower limit of the younger bin. Thus, each bin contains enough signal in the CMD that if the bin were removed, the fit to the data would be significantly degraded. We note that for the optical and UV fits, we adopted the time bins measured from the
IR fits because the optical and UV data were not sensitive enough to the old stellar populations to provide cumulative distributions.

4. RESULTS

4.1. Star Formation History

The resulting SFHs for our CMD fits to the four regions are shown in Figure 5. The UVIS data did not provide sufficient depth to probe ages greater than ~200 Myr, and thus no points are plotted for older ages. Cumulative plots of the stellar mass formed are shown in Figure 6, and the results for all regions are overplotted in Figure 7. Since the UVIS data were not sensitive to old populations, we could not generate cumulative SFHs from the UVIS data.

The SFHs show that in all of the areas observed, the majority of the stellar population is old. In the central portion of the galaxy, the relatively shallow data are able to constrain the population only weakly, putting a lower limit of >80% of the stellar mass having ages >4 Gyr. In the outermost (and deepest) field, the constraint is tighter, with >74% of the stellar mass having ages >8 Gyr. Taking uncertainties into account, all of our data are consistent with this constraint from the deepest photometry.

The consistency of all of our data, from the optical to the IR and from the center to the outskirts of the disk, with more than three quarters of the stellar mass being very old, is surprising. This galaxy is well known for being a young starburst galaxy—a “Wolf–Rayet” galaxy (Sargent & Filippenko 1991). While the current starburst is already known to be responsible for only a few percent of the stellar mass (Huchra et al. 1983), it is still surprising that such a small percentage of the population is young (<1% in the past 50 Myr and <4% in the past Gyr), and that such a high percentage is very old. Overall, the galaxy has evolved very little since z ~ 1, as shown in our plot of the surface density profile over the past 6.3 Gyr (Figure 8).

Our measurements also provide some indication of the metallicity of the stellar populations in NGC 4214. Overall, the mean metallicity of the populations fell in the range of −1.6 < [M/H] < 0, with the old population being −1.6 < [M/H] < −0.6 in the IR data and −1.4 < [M/H] < −0.6 in the WFPC2 data, and the young population being −0.5 < [M/H] < 0 in the UVIS data. The WFPC2 data had very little sensitivity to metallicity for the young population, as MS stars of different metallicities have very similar colors in F606W−F814W.

4.2. The Young Stellar Population

The old population likely dominates at all radii, suggesting that this population is well mixed and NGC 4214 is old. However, the young stellar populations are not well mixed, as their density clearly varies significantly with their position in the galaxy. This difference can be seen by looking at the strong core He-burning sequence extending vertically from the tip of the RGB in the central WFC3/IR CMD and northern WFPC2 CMD, which is relatively absent in the northwest WFPC2 CMD. The central starburst is evident, even when the population is probed only in the IR, where massive young stars are faint, although we note that the very youngest population (<10 Myr) in the innermost region is not reliably measured in the IR (Figure 5). The SFH of the innermost region of the galaxy is the only one with a sustained recent (~30 Myr) SFR that is higher than any rate in previous epochs. This result does not mean that the rate is higher than it has ever been in the past, since our time resolution would not allow us to detect short, strong bursts at ancient times, but the result does show that very recent star formation near the galaxy center is at least a factor of two higher than the average rate over the galaxy’s history. Just outside of this central starburst, the SFR is slightly less than the...
Figure 6. Cumulative formation of stellar mass calculated from the SFHs of our fields. The central WFC3 field has been broken up into an inner region and an outer region, shown in the top two panels. The UVIS data did not constrain the cumulative formation because it contained no significant information concerning stars older than 200 Myr.

Figure 7. All cumulative formation histories overplotted. Darker shades of gray represent overlaps in the cumulative SFHs at different radii. All of our measurements are consistent with 75% of the stellar mass forming by z ~ 1. The best-fit solutions are shown with colored lines (orange = N4214_NW_WFPC2, green = N4214_N_WFPC2, blue = N4214_OUTER_IR, purple = N4214_INNER_IR).

(A color version of this figure is available in the online journal.)

Figure 8. Cumulative stellar mass density profile of NGC 4214 at three epochs, as calculated from our SFH measurements. Changes in the IMF and/or mass cutoff could shift all of the surface density data up or down. The scale lengths are unaffected by these IMF issues.

(A color version of this figure is available in the online journal.)
Figure 9. Locations of the massive (>12 $M_\odot$) young stars in our images. Bluer colors indicate more massive (luminous) stars (red = 12–22 $M_\odot$; yellow = 23–34 $M_\odot$; green = 35–40 $M_\odot$; blue = 41–48 $M_\odot$; cyan = 49–56 $M_\odot$; white = ~56 $M_\odot$).

Figure 10. Locations of the massive (>12 $M_\odot$) young stars in the vicinity of a star-forming knot in our WFPC2 field, north of the galaxy plotted on the SDSS color image (left) and our F606W WFPC2 image (right). Annuli mark our radial bins to search for a correlation between age and distance from the knot’s center. Colors are the same as in Figure 9.
overall mean rate but higher than the mean rate over the past several gigayears.

Outside of the central WFC3 field, the knots of star formation in the northern WFPC2 field are easily seen in the CMD. Recent star formation produces both the strong red He-burning sequence extending brightward from the RGB and the well-populated upper MS. The SFH shows a strong increase in SFR starting 100 Myr ago with a prominent peak at very recent times (5–12 Myr ago), providing some indication of the age of these features. Prior to 100 Myr ago, our analysis shows that these regions of NGC 4214 were relatively quiescent, perhaps bearing resemblance to an early-type dwarf.

In Figure 9 we plot the spatial distribution of young stars as a function of brightness. The brightest (youngest) stars appear to be more tightly clustered than the fainter stars. A two-dimensional K-S test yields only a 4% probability that the brightest MS stars (cyan and white diamonds in Figure 9) and the faint MS stars (red diamonds in Figure 9) are drawn from the same spatial distribution. Thus, the stars have likely migrated significantly from their birth locations on timescales of just ~12 Myr (the MS lifetime of a 12 M☉ star).

To gain a sense of the velocities with which stars are spreading from their birth regions, we looked for a good example region to study in detail. One of the knots of star formation (R.A. = 183.8884, decl. = 36.3683; see Figure 10) was isolated enough to look for a correlation between the magnitude of the brightest MS stars and the distance from the center of the knot. Taking the brightest MS star in annuli of 0′–6′, 6′–8′, 8′–10′, and 10′–12′ (see Figure 10), there is a weak correlation between the magnitude of the brightest MS star and its distance from the central knot. Each 75 pc farther out, the brightest MS star is ~1 mag fainter. If we assume that the brightest MS star is a proxy for the MS turnoff magnitude, at these bright magnitudes on the upper MS, 1 mag of luminosity roughly corresponds to 10 Myr of age. If we further assume that the weak correlation is real and due to the diffusion of stars produced in the center of the knot, the slope of the correlation is consistent with a diffusion speed of ~8 pc Myr⁻¹ (~8 km s⁻¹). This value is similar to the velocity dispersion of B stars in the Milky Way disk (Dehnen & Binney 1998) and the diffusion speed found for an outer spiral arm in M81 (Williams et al. 2009b).

The brightest MS stars in our catalog provide diagnostic tests for massive stellar evolution models. HST UV spectroscopy has been measured for the central starburst, yielding an age of 4–5 Myr (Leitherer et al. 1996). Our photometry reveals point sources with F336W (U-band equivalent) magnitudes of ~17.6, which is $M_{F336W} = -9.9$ at the distance and extinction of NGC 4214. We show our F336W – F438W CMD in Figure 2 along with the isochrone for an age of 4 Myr and a metallicity of [M/H] = −0.4, shifted to the distance and foreground extinction of NGC 4214. Assuming these objects are not unresolved compact clusters, these bright stars are consistent with the brightest blue portion of this isochrone, which represents model stars with masses of 52–56 M☉. The low foreground extinction ($A_V = 0.07$) and good agreement between the data and the model isochrone suggests that these stars are not strongly affected by extinction internal to NGC 4214. NGC 4214 is known to contain only a modest amount of internal extinction (internal GALEX FUV extinction ~0.58 mag; Lee et al. 2009), and these particular UV-bright stars are apparently between us and any significant dust within NGC 4214, making them easily detected and measured in the UV.

Finally, we estimated the approximate total SFR for the galaxy over the past ~100 Myr, as it has been relatively high during most of this period. If we add together the SFRs from our four regions, we obtain a total rate of ~0.1 M☉ yr⁻¹, ~80% of which is in the central UVIS field. This rate is consistent with the SFR recently measured for NGC 4214 from HST/WFPC2 photometry by McQuinn et al. (2010a, 2010b).

4.3. Dominant Galaxies in Their Environment

Interestingly, the overall population is similar to that of the very different nearby dwarf galaxy, NGC 404, which is a somewhat more massive S0 galaxy (~4.5 × 10^10 M☉; Karachentsev et al. 2004) with very little recent star formation. The ANGST data for that galaxy show that outside the inner regions ~90% of the stellar population is ~8 Gyr old and ~75% is ~10 Gyr old (Williams et al. 2010). While the overall stellar populations of NGC 404 are older than those of NGC 4214, the difference is not overwhelming. In fact, by 4 Gyr ago, both galaxies had formed 90% or more of their stellar mass. Apparently, the vast difference in morphology between these two galaxies is mainly due to only a small percentage of the stellar mass. Our results show that ~1% of the stellar mass in NGC 4214 formed in the past ~100 Myr. The percentage of stellar mass formed in the past 100 Myr is much smaller in NGC 404, only ~0.1% outside of the galaxy center. However, there is evidence for a 1 Gyr old starburst in the center of NGC 404 (Seth et al. 2010); about 1 Gyr ago NGC 404 may have more closely resembled NGC 4214’s present-day appearance. While this difference represents a small percentage of the total stellar populations of the galaxies, it results in their vastly different morphological classifications.

Both NGC 4214 and NGC 404 appear to have older median ages than some more massive disks, such as M33 (Williams et al. 2009a). Perhaps their old stellar ages are somehow due to their relationship with their environments. Both galaxies are the most massive in their local environment. Perhaps it is common for the dominant galaxy by mass within any group of galaxies (where NGC 404 is isolated, making its own “group”) to be dominated by ancient stars. If this effect is indeed common, it may indicate that the most massive galaxy in a group dominates gas accretion in the early stages of evolution, winning the local “downsizing” battle to be the dominant star-forming object during the epoch of formation.

5. CONCLUSIONS

We have analyzed deep HST/WFPC2 photometry of the NGC 4214 disk and HST/WFC3 photometry of the central portion of NGC 4214. Full CMD modeling of the photometry shows that the stellar populations throughout the disk are old, with ~75% of the stellar mass older than ~8 Gyr. This result shows that overall the stellar populations of NGC 4214 are similar to those of the S0 galaxy NGC 404, other than the youngest 1% of the stellar mass, which formed in the past 100 Myr in NGC 4214. The similarity suggests that a few hundred megayears ago, NGC 4214 may have looked very similar to NGC 404 today, though NGC 4214 may have been more gas-rich. Alternatively, NGC 4214 may have recently acquired gas from a merging satellite, such as the merger suggested by Fanelli et al. (1997). NGC 4214 currently has more than 10 nearby satellites (e.g., Dalcanton et al. 2009, their Figure 2); therefore, such an alternative is a strong possibility. Finally, we presented an argument that because both galaxies are
the dominant members of their local environments, they were in favorable positions to form such a high percentage of their stars so early.

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