THE HISTORY OF STAR FORMATION IN GALAXY DISKS IN THE LOCAL VOLUME AS MEASURED BY THE ADVANCED CAMERA FOR SURVEYS NEARBY GALAXY SURVEY TREASURY

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ABSTRACT

We present a measurement of the age distribution of stars residing in spiral disks and dwarf galaxies. We derive a complete star formation history of the ∼140 Mpc1 covered by the volume-limited sample of galaxies in the Advanced Camera for Surveys (ACS) Nearby Galaxy Survey Treasury (ANGST). The total star formation rate density history (ρSFR(t)) is dominated by the large spirals in the volume, although the sample consists mainly of dwarf galaxies. Our ρSFR(t) shows a factor of ∼3 drop at z ∼ 2, in approximate agreement with results from other measurement techniques. While our results show that the overall ρSFR(t) has decreased since z ∼ 1, the measured rates during this epoch are higher than those obtained from other measurement techniques. This enhanced recent star formation rate appears to be largely due to an increase in the fraction of star formation contained in low-mass disks at recent times. Finally, our results indicate that despite the differences at recent times, the epoch of formation of ∼50% of the stellar mass in dwarf galaxies was similar to that of ∼50% of the stellar mass in large spiral galaxies (z ≥ 2), despite the observed galaxy-to-galaxy diversity among the dwarfs.

Key words: cosmology: observations – galaxies: evolution – galaxies: stellar content

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The star formation history (SFH) of the universe (ρSFR(t)) constrains models of structure formation, the assembly of galaxies, metal production, and the epoch of reionization. Currently there are testable models for the growth of structure in the universe on all scales, for the flow of gas in and out of galaxies, and the conversion of gas into stars. If these models are correct, then we should expect consistency between the models and observations of the rate at which galaxies formed stars throughout cosmic time at all galaxy mass scales. Moreover, we should expect a similar level of consistency between the observed in situ star formation rate (SFR) and the stellar record and metal content of the universe at the present day.

With the combination of Hubble Space Telescope (HST), large aperture redshift surveys, and well-calibrated photometric redshifts, there has been an explosion of observational constraints on the SFR at high redshifts (e.g., Madau et al. 1996; Connolly et al. 1997; Lilly et al. 1996; Steidel et al. 1999; Fontana et al. 2003; Iwata et al. 2003; Bunker et al. 2004; Giavalisco et al. 2004), now pushing out to z ∼ 8 (Bouwens et al. 2010). These measurements have been augmented by measurements of the obscured SFR due to advances in the capabilities of long wavelength detectors allowing measurements of high-z star formation (Chapman et al. 2005). Such assessment of the SFR has also been made at low redshifts by surveys such as the Sloan Digital Sky Survey (SDSS; Heavens et al. 2004) and the Galaxy Evolution Explorer (Schiminovich et al. 2005) all on the basic properties of SFR versus time.

While early measurements of ρSFR(t) showed a peak around z ∼ 1.5 (e.g., Madau et al. 1996; Connolly et al. 1997; Hopkins et al. 2001), more recent measurements have generally put the peak prior to z ∼ 2 (e.g., Lanzetta et al. 2002; Hopkins 2004; Chapman et al. 2005; Bouwens et al. 2007; Reddy et al. 2008), including measurements combining the SFHs of Local Group (LG) galaxies. Inside the LG Hopkins et al. (2001) found that ρSFR(t) was broadly consistent with redshift surveys with no significant contribution from dwarfs at any epoch, and Drozdovsky et al. (2008) found an excess of star formation in recent epochs, dominated by the disk of the Milky Way, as well as a recent increase in the contribution from dwarfs. Weisz et al. (2011b) found little difference in the SFHs of the LG dwarfs and those in a larger volume. Only one recent measurement, based on integrated galaxy spectra in the SDSS (Heavens et al. 2004), has found a peak more recent than z = 2. Furthermore, recent analytical calculations (Hernquist & Springel 2003), semi-analytic galaxy formation models (Lacey et al. 2010), and hydrodynamic simulations (Springel & Hernquist 2003) also generally put the peak earlier than z ∼ 2. For current Wilkinson Microwave Anisotropy Probe (WMAP) cosmology, this places the peak at look-back times >10 Gyr. There is mounting evidence that low-mass galaxies may have later formation times (i.e., “down-sizing;” Cowie et al. 1996; Lilly et al. 2003; Thomas et al. 2005; Neistein et al. 2006, and many others), which could in principle affect the location of the ρSFR(t) peak. Unfortunately, direct constraints at high redshift are challenging, given that all

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in situ redshift-based studies have magnitude limits that prohibit the inclusion of low-mass galaxies in their measurements.

Herein, we report our measurement $\rho_{\text{SNR}}(1)$ in our local volume using resolved stellar populations from a volume-limited sample of galaxy disks: the largest ever measured using resolved stellar populations analysis. Our approach has the benefit that we simultaneously explore the past SFH and the present stellar record. Moreover, we have complete, volume-limited sampling of the galaxy population down to very low masses, rather than the high-mass galaxies that dominate in situ high-redshift studies. The limitations of the approach are difficulty resolving stars in massive spheroids, so that we can only trace the SFH of disks and dwarf galaxies, and a relatively short distance over which stars can be resolved with $HST$, so that we cannot measure a truly representative volume of the universe. Our results are generally consistent with those of recent redshift surveys, and we conclude that with the currently possible depth of resolved stellar photometry over this volume, we cannot resolve the age of the peak beyond placing it at $z > 2$.

2. DATA ACQUISITION, REDUCTION, AND ANALYSIS

All of the data for this study were analyzed through the Advanced Camera for Surveys (ACS) Nearby Galaxy Survey Treasury (ANGST; GO-10915) and ACS Nearby Galaxies; Reduce, Reuse, Recycle (ANGRRR; AR-10945) programs. 9 Our full sample is detailed in Table 1 and in Dalcanton et al. (2009). The motivation for the sample selection was to stay within a limited volume. We have included all galaxies inside of $\sim 3.5 \text{ Mpc}$, but outside the LG (as defined by van den Bergh 2000; $\sim 8 \text{ Mpc}^3$) and more than 20° from the Galactic plane ($\sim 34\%$ of the sphere). ANGST extended this distance limit to $\sim 4 \text{ Mpc}$ in the direction of the M81 group and Sculptor filament to improve sampling of massive galaxies and dense environments. The Cen A group, which is also within $\sim 4 \text{ Mpc}$, was excluded due to its low galactic latitude and incomplete galaxy census. Our sample therefore covers only $\sim 70\%$ of the stellar mass in the volume between $3.5$ and $4.0 \text{ Mpc}$, making our effective distance limit $\sim 3.8 \text{ Mpc}$. Therefore, our net volume surveyed is $\sim 140 \text{ Mpc}^3$. This scale is smaller than the large-scale structure of the universe, and thus we may be sampling a non-representative environment. Therefore, differences between our results and those of redshift surveys may be primarily due to such sampling effects.

We exclude KDG73 and Sc22 as their revised distance moduli place them beyond 4 Mpc, and we exclude BK6N and KKH57 due to poor data quality. The program obtained ACS and WFPC2 imaging of a volume-limited sample of galaxies. All photometry techniques are described in detail in Dalcanton et al. (2009) and K. Gilbert et al. (2011, in preparation). In short, the photometry and artificial star tests were measured simultaneously for all of the objects in the uncombined images using the software packages HSTPHOT and DOLPHOT (Dolphin 2000), and the output data were culled on signal-to-noise ratio, sharpness, and crowding.

2.1. SFH Determination

We measured the SFR and metallicity as a function of stellar age using the software package MATCH (Dolphin 2002). We fit the observed color–magnitude diagrams (CMDs; with magnitude cuts set to limits provided in Table 1) by populating the stellar evolution models of Girardi et al. (2002; with updates in Marigo et al. 2008) with a Salpeter (1955) initial mass function (IMF). We fixed the distance and reddening to the Dalcanton et al. (2009) values. The best fit provides the relative contribution of stars of each age and metallicity in each field.

We then performed Monte Carlo fits by resampling the best-fitting model 100 times. Then, when fitting the realizations, the systematic errors are accounted for by introducing small random shifts in the bolometric magnitudes and effective temperatures of the models. These shifts are introduced at the level of the differences between models in the literature, and therefore serve as a proxy of the effects of our choice of stellar evolution models. From these tests we calculated our uncertainties due to Poisson sampling, 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.

Our time bins were chosen based on the features present in most of our data. In general, the main-sequence and blue He-burning sequences provide high resolution time sensitivity for times more recent than $\sim 400 \text{ Myr}$. After this epoch, our photometry contains only the red giant branch, which contains degeneracies between age and metallicity (Gallart et al. 2005), the asymptotic giant branch, which is generally poorly populated and suffers from poorly constrained models (Melbourne et al. 2010), and the red clump, which is dominated by old ($\geq 2 \text{ Gyr}$) stars. We therefore limited ourselves to four bins in this large interval: one long bin on each side of $\sim 1 \text{ Gyr}$ ago (the epoch where our CMDs provide the least information) in order to leverage more reliable age information from before and after this period, and two more bins where we have additional information from the red clump to help constrain the age distribution (4–10 Gyr and 10–14 Gyr).

When determining the SFHs, we check the effects of our varying depth and magnitude cuts for fitting each CMD. Due to the failure of ACS during the ANGST program, our photometry sample is heterogeneous and of varying depth (see Table 1). Nevertheless, the bulk of the stellar mass is in M81 and NGC 253, which were both observed with ACS, and every

| Galaxy | Proposal | Target | Camera | Filter | Exposure (s) | Stars | $m_{30}^\text{00}$ | $M_{30}^\text{00}$ |
|--------|----------|--------|--------|--------|-------------|-------|----------------|----------------|
| Antlia/P29194 | 10210 | ANTLLIA | ACS | F606W | 985 | 19226 | 28.01 | 2.18 |
| Antlia/P29194 | 10210 | ANTLLIA | ACS | F814W | 1174 | 19226 | 27.30 | 1.54 |
| KK230 | 9771 | KK230 | ACS | F606W | 1200 | 4679 | 28.15 | 1.69 |
| KK230 | 9771 | KK230 | ACS | F814W | 900 | 4679 | 27.08 | 0.64 |
| E410-005/KK3 | 10503 | ESO410-005 | ACS | F606W | 8960 | 79952 | 28.85 | 2.39 |
| E410-005/KK3 | 10503 | ESO410-005 | ACS | F814W | 22400 | 79952 | 27.92 | 1.48 |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
attempt was made to obtain a depth reaching the red clump feature in the CMD for all galaxies observed with WFPC2 ($M_{F814W} \sim -0.3, M_{BP606W} \sim 0.4$). Furthermore, our SFHs for ancient times ($>2$ Gyr) were always taken from the deepest data available, which for most low-mass galaxies included information from the red clump feature (see Table 1 and Figure 1). There is still no guarantee that our data were all detailed enough to reliably separate populations with ages slightly less than 10 Gyr from those with ages slightly greater than 10 Gyr.

2.2. SFH Scaling

Our fields cover only a portion of each galaxy, making it necessary to scale the measured SFH to the total galaxy mass. Once we had measured the SFHs for the deepest available field in each ANGST galaxy, we renormalized the SFRs to a Kroupa (2002) IMF (divided by 2) and scaled them to the total stellar mass in each galaxy. We first estimated the galaxy’s total stellar mass from Spitzer photometry (see below). The stellar mass contained in our ANGST field was then calculated directly from our SFH. The quotient of these provided our estimate of the fraction of the galaxy’s stellar mass contained in our field ($\text{SFR}_{\text{field}}(t) / \text{M}_{\text{star},SFH}$).

To estimate each galaxy’s total stellar mass, we used the total Spitzer 3.6 $\mu$m luminosity from the Spitzer Local Volume Legacy Survey (Dale et al. 2009). To determine the appropriate $M/L_{3.6\mu}$ to apply, we calculated $M/L_{3.6\mu}$ using stellar masses determined by our CMD fits and Spitzer 3.6 $\mu$m photometry of the fields with good Spitzer coverage and minimal foreground contamination. In all cases with reliable Spitzer data covering our field, $M/L_{3.6\mu} = 0.5 \pm 0.2$. We therefore assumed $M/L_{3.6\mu} = 0.5$ to estimate each galaxy’s total stellar mass. We verified that this assumption resulted in a total stellar masses of M81 and NGC 253 less than the mass calculated from their rotation curves (as taken from Puche et al. 1991; Adler & Westpfahl 1996). For large spirals, the total stellar mass was further scaled by the galaxy’s disk/(bulge+disk) luminosity ratio from the literature to avoid representing stellar mass in the bulge with the SFH of the disk.

For the largest ANGST galaxies, most of the young ($<2$ Gyr) populations are not well mixed and are not contained within a single ANGST field. Thus, our assumption that the SFH in the deepest field (which is located in the outer regions of the disk, where crowding is minimized) is representative of the entire galaxy is not valid at recent timescales that do not allow sufficient radial mixing. In these cases, we therefore made use of shallower tilings that covered at least half of the optical disk. Where possible (M81, NGC 253, NGC 55, and NGC 3109), we measured the recent SFHs ($<2$ Gyr; $z < 0.2$) from the shallower galaxy tilings. These tilings cover the full extent of the optical disk of M81 and half of the optical disk of the other three galaxies (stepping along the major axis from the center). This method provides a more realistic total recent SFH for these large disk galaxies, requiring less scaling. The case of M81 required no scaling, and the other three galaxies required scaling only by a factor of two to account for the ANGST coverage. However, since a significant amount of star formation may be in unresolved clusters of stars and extincted by dust, we still likely miss some fraction of the most recent star formation. We verified that the recent SFRs obtained by this method were at least equal to the rates that would have come out of scaling.

Figure 1. Histogram of the 50% completeness limiting F814W absolute magnitude for the sample galaxies. These values have been corrected for distance and extinction. The depth of 58% is fainter than the red clump in our M81 data (thick gray line).
the SFH of the deep field by the total Spitzer stellar mass of the
galaxy in order to be sure that using the shallow tiled data was,
at the very least, not reducing the amount recent star formation
contained in these galaxies.

We note our measuring technique is not sensitive to the stellar
populations in bulges. Because of severe crowding in the central
portions of the large galaxies, the photometry was too shallow
to produce reliable SFHs and was therefore not included. The
galaxy most strongly under-represented due to this bias against
bulges is M82, which is known to have a total current SFR
galaxy most strongly under-represented due to this bias against
produce reliable SFHs and was therefore not included. The
portions of the large galaxies, the photometry was too shallow
contained in these galaxies.

As shown in Figure 2, M82 is disproportionately responsible for the high
SFR \( \sim 1-4 \) Gyr ago.

3. RESULTS

Our volume-limited \( \rho_{\text{SFR}}(t) \), along with the contributions of
some major components (spirals, dwarfs, M81, and NGC 253),
is shown in Figures 2 and 3. Overall, \( \rho_{\text{SFR}}(t) \) in the local volume
is clearly dominated by that of the large spirals NGC 253 and
M81. In Figure 4, we plot \( \rho_{\text{SFR}}(t) \), scaled to match the cosmic
mean stellar density, along with a compilation of literature studies
(Hopkins 2004, 2007; Reddy et al. 2008; Heavens et al.
2004), the LG (Drozdovsky et al. 2008), and two theoretical
studies (Lacey et al. 2010; Springel & Hernquist 2003). The
models are not easily compared to our results because most of
our time resolution comes at epochs more recent than \( z = 1 \) whereas the models typically provide one data point per unit
redshift. However, overall it is encouraging that our results
are similar to the observational results already in the literature,
determined using other techniques, that our results are similar to
the SFH of the LG, and that our results fall within the wide range
of theoretical calculations. We note that our result differs from

Figure 2. Top left: the SFR density of the local volume. Error bars show the scaled root-sum-squared of the uncertainty estimates from our measured SFHs (Section 2.1). Histograms denote combined \( \rho_{\text{SFR}}(t) \) including all 54 dwarf galaxies in the sample (blue), eight of the spiral disks (all but M82, M81, and NGC 253), M82 alone (green), M81 alone (yellow), and, completing the sample, NGC 253 alone (red). Other panels: same as top left but with linear look-back time (top right), linear SFR (bottom left), and both (bottom right). We adopt a five-year WMAP (Dunkley et al. 2009) cosmology for all conversions between time and redshift.

(A color version of this figure is available in the online journal.)
Figure 3. Fractional contribution of several components to the total SFH of the survey volume. Colors are the same as in Figure 2.
(A color version of this figure is available in the online journal.)

Figure 4. Black error bars: $\rho_{\text{SFR}}(t)$ measured from the ANGST sample. Values have been scaled to reproduce the mean cosmic stellar density for relevant comparison. Color error bars: measurements taken from the compilation of Hopkins (2004; with updates from in Hopkins 2007) and the results of Heavens et al. (2004), Reddy et al. (2008), and Bouwens et al. (2010). Dotted error bars: measurements taken from the LG study of Drozdovsky et al. (2008), scaled by a factor of three to compensate for the overdensity of the LG. Lines: theoretical predictions from semi-analytic galaxy evolution calculations (blue; Lacey et al. 2010) and hydrodynamic simulations (red; Springel & Hernquist 2003).
(A color version of this figure is available in the online journal.)
those of Heavens et al. (2004), who analyzed spectra of $\sim 10^5$ nearby galaxies and found the local $\rho_{\text{SFR}}(t)$ peak at $z \sim 0.6$. While both measurements show enhanced star formation at look-back times of $\sim 2–6$ Gyr, the discrepancy is in the $z > 2$ ($>10$ Gyr) bin, where our measured rate is a factor of three larger than theirs, placing our peak rate in this oldest bin. Their sample and technique remain the only ones to have measured such a low rate for $z > 2$.

Despite the diversity of SFHs in local dwarf galaxies ($M_B > -18$, Weisz et al. 2011a), when one sums their total $\rho_{\text{SFR}}(t)$, it is remarkably similar to that of the full galaxy sample prior to $z \sim 0.1$ ($>1$ Gyr look-back time). For all but this recent epoch, the $\rho_{\text{SFR}}(t)$ pattern for the dwarfs is indistinguishable from that of the large spirals, which, in turn, is indistinguishable from that of the sample volume. Therefore, we do not detect any significant difference between the formation times of dwarf galaxies and large spirals, suggesting that any differences occurred prior to $z \sim 2$ ($>10$ Gyr ago). At look-back times $\gtrsim 4$ Gyr ($z \gtrsim 0.5$), our total SFRs are indistinguishable from those of most redshift surveys. However, our recent SFRs are higher than those of redshift surveys, similar to those of the LG (Drozdovsky et al. 2008). This result is largely due to our inclusion of low-mass galaxies (other spirals and dwarfs in Figures 2 and 3), which contribute 50% of the SFR at recent times. Such low-mass galaxies are typically not included in redshift surveys due to their low luminosities.

4. CONCLUSIONS

We have derived $\rho_{\text{SFR}}(t)$ for galaxy disks in our local volume using resolved stellar photometry. This measurement includes the contribution by different galaxy types. Our sample is dominated, in number, by galaxies fainter than the limits of any available redshift survey or high-z HST imaging. Thus, our $\rho_{\text{SFR}}(t)$ represents a portion of parameter space not yet studied in detail outside the LG. However, our sample is lacking in massive spheroids, whose mean $\rho_{\text{SFR}}(t)$ is more reliably determined from the large samples included in redshift surveys and high-z HST imaging.

We find that, while $\rho_{\text{SFR}}(t)$ is dominated by that of the spirals, the overall shape of the measurement is robust against removal of any single galaxy. We also find that the combined $\rho_{\text{SFR}}(t)$ of the dwarf galaxies is not significantly different in shape from that of the larger spirals except for the most recent $z > 2$. This result is consistent with those of Thomas et al. (2005) for high-density environments.

We have compared our measurements to those obtained by galaxy surveys and analysis of the Hubble Deep Field and Ultra Deep Field. We find overall agreement between our results and those of galaxy surveys; however, our measurements do not yet have the time resolution at epochs prior to 10 Gyr ($z > 2$) to resolve the peak in cosmic SFR density. Our measurements suggest that this peak lies prior to $z \sim 2$, consistent with the most recent HST/WFC3 results, which place the peak at $z \sim 4$ (Bouwens et al. 2010). Finally, at recent times, the contribution of low-mass galaxies to the total SFR has increased, resulting in a higher total rate at recent times than observed by other methods.

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