LEO A: A LATE-BLOOMING SURVIVOR OF THE EPOCH OF REIONIZATION IN THE LOCAL GROUP

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ABSTRACT

As part of a major program to use isolated Local Group dwarf galaxies as near-field probes of cosmology, we have obtained deep images of the dwarf irregular galaxy Leo A with the Advanced Camera for Surveys aboard the Hubble Space Telescope. From these images we have constructed a color-magnitude diagram (CMD) reaching apparent [absolute] magnitudes of \((M_{B}/M_{V}) \simeq (29.0 \pm 4.4, 27.9 \pm 3.4)\), the deepest ever achieved for any irregular galaxy beyond the Magellanic Clouds. We derive the star formation rate (SFR) as a function of time over the entire history of the galaxy. We find that over 90% of all the star formation that ever occurred in Leo A happened more recently than 8 Gyr ago. The CMD shows only a very small amount of star formation in the first few billion years after the big bang; a possible burst at the oldest ages cannot be claimed with high confidence. The peak SFR occurred \(\approx 1.5–4\) Gyr ago, at a level 5–10 times the current value. Our modeling indicates that Leo A has experienced very little metallicity evolution; the mean inferred metallicity is consistent with measurements of the present-day gas-phase oxygen abundance. We cannot exclude a scenario in which all of the ancient star formation occurred prior to the end of the era of reionization, but it seems unlikely that the lack of star formation prior to \(\approx 8\) Gyr ago was due to early loss or exhaustion of the in situ gas reservoir.

Subject headings: galaxies: dwarf — galaxies: evolution — galaxies: individual (DDO 69)

1.INTRODUCTION

Dwarf galaxies are the most common class of galaxy in the universe, which gives them significance far beyond their mass. They are simpler in structure and perhaps more easily understood than giant galaxies, and so their study can shed light on the processes governing galaxy evolution. Dwarf galaxies are also important to cosmology, because they are similar in mass to predictions for the protogalactic fragments that collapse hierarchically to form giant galaxies. One of the most interesting testable predictions to come from numerical simulations of galaxy formation in a cold dark matter (CDM) cosmology is that after the universe is reionized at redshifts \(z \gtrsim 6\), galaxies of total mass \(\lesssim 10^{10} \, M_{\odot}\) are prevented from further accretion of gas by photoionization feedback from the cosmic ultraviolet background (e.g., Navarro & Steinmetz 1997). This may strongly impact a dwarf’s evolution, but observational evidence is inconclusive.

We are fortunate to have a plethora of dwarf galaxies available to study in the Local Group; their proximity makes it possible to measure their histories in far more detail than is possible in even the next-closest groups. Because the relative importance of mergers and interactions as compared to intrinsic properties is not well known, it is important to study dwarfs in as many environments as possible. Therefore, we have begun a Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) program to measure the complete star formation histories (SFH) of six isolated Local Group dwarf galaxies in order to search for the imprints of cosmological processes on their evolution: the LCID (Local Cosmology from Isolated Dwarfs) project (C. Gallart et al. 2007, in preparation). By measuring several small, isolated galaxies, we will test for correlations and patterns in their SFH that may provide clues as to the magnitude of the effects of reionization, supernova blow-out, and other feedback processes.

Here we present our first results, a new measurement of the SFH of the galaxy Leo A (DDO 69). Leo A was discovered by Zwicky (1942) in the course of a search for the lowest luminosity galaxies. It is indeed one of the least luminous gas-rich galaxies known (e.g., Mateo 1998). The vital statistics of Leo A are given in Table 1. Leo A is a small, blue galaxy conspicuous for its population of young, massive stars, with estimated ages from \(\approx 10^{7}\) to \(\approx 10^{8}\) yr (Demers et al. 1984; Tolstoy 1996). The star formation rate (SFR) has apparently declined since that time, although a few small H\(\alpha\) regions are present. The first HST observations of Leo A (Tolstoy et al. 1998) revealed a very high fraction of stars aged \(\approx 1–2\) Gyr at very low metallicity, suggesting that only \(\approx 10\%\) of the stellar mass was contained in older stars. Schulte-Ladbeck et al. (2002) obtained slightly deeper data in an offset field and measured a lower overall SFR and much higher fraction of ancient stars: they found evidence for a median age of \(\approx 4\) Gyr, with the bulk of the old stars older than \(\approx 10\) Gyr. Neither of these studies reached the necessary depth to convincingly measure the fraction and age distribution of the oldest stars. Dolphin et al. (2002) supplied the first proof of the existence of truly ancient stars in Leo A with the discovery of RR Lyrae type variables. Our goal here is to provide a definitive measurement of how Leo A’s SFR has varied with time over its entire lifetime. Further details, including spatial patterns within Leo A, com-
TABLE 1

global properties of leo a

| Quantity | Value | References |
|----------|-------|------------|
| Galactic coordinates \((l, b)\) (deg) | 196.9, +52.4 | 1 |
| Distance modulus \((m - M)_B\) | 24.5 ± 0.1 | 2 |
| Reddening \((E(B - V)\) | 0.021 | 3 |
| Absolute magnitude \(M_B\) | −11.7 ± 0.2 | 4 |
| \(M(H\ i) (10^{10} M_\odot)\) | 1.1 ± 0.2 | 5 |
| Total mass \((10^{10} M_\odot)\) | ≤20 | 5 |
| 12 + log \((\text{O/H})\) | 7.38 ± 0.1 | 6 |
| Holmberg semiaxes, \(a_p, b_p\) (arcmin) | 3.5, 2.2 | 7 |
| Star formation rate \((M_\odot \text{yr}^{-1})\) | \((1 - 2) \times 10^{-4}\) | 8, 9 |

REFERENCES.—(1) NASA/IPAC Extragalactic Database; (2) Dolphin et al. 2002; (3) Schlegel et al. 1998; (4) de Vaucouleurs et al. 1991; (5) Young & Lo 1996; (6) van Zee et al. 2006; (7) Fisher & Tully 1975; (8) Hunter & Elmegreen 2004; (9) James et al. 2004.

Comparison to numerical models, and thorough comparison to other galaxies in our sample, will be deferred to future papers, in preparation.

2. DATA ACQUISITION AND PHOTOMETRY

Leo A was observed with ACS over 16 orbits during the time period 2005 December 26 to 2006 January 8. Each HST orbit was devoted to a single exposure of at least 2400 s duration, split to facilitate cosmic-ray removal. We chose the filter pair F475W (Sloan \(g\)) and F814W (Broad I) as having the best combination of throughput and temperature sensitivity for F–G type dwarfs. Our paramount concern in designing the observations was to achieve the maximum possible depth of photometry, so that our conclusions would be as free as possible from difficult-to-characterize systematics. We used small dithers between exposures to allow us to correct for hot pixels in the detector and observed when the Sun-target angle was over 100°. The total exposure time in \((F475W, F814W)\) was \((19,200, 19,520)\) s.

The Leo A field is shown in Figure 1, where the left panel shows a mosaic of images from the Sloan Digital Sky Survey (SDSS; fourth data release; Adelman-McCarthy et al. 2006), centered on the galaxy. The footprint of our ACS observation is marked by the red square, while the cyan ellipse shows the approximate location of the Holmberg radius. It is important to remember that a low surface density sheet of red giant stars extends out to \(\approx 7.5'\) (Dolphin et al. 2002; Vansevičius et al. 2004), and in the outer reaches of the galaxy the ratio of young to old stars must be significantly lower than what we find here for the center of Leo A.

The pipeline-processed data were combined using MultiDrizzle to eliminate cosmic rays and photometered using DOLPHOT, a version of HSTPHOT (Dolphin 2000) incorporating the best available ACS calibrations. Extended objects and residual hot pixels were rejected based on their brightness profiles, leaving 112,000 well-measured stars in the color-magnitude diagram (CMD). Artificial star tests show that the typical photometric error reaches ±0.1 mag for \((m_{475}, m_{814}) = (28.7, 27.9)\); the 50% completeness limit is at \((m_{475}, m_{814}) = (29.0, 27.9)\).

The CMD is shown in Figure 2. Where the density of stars is high enough to confound the easy estimation of the relative number of stars in the various sequences, we have plotted contours corresponding to stellar density rather than individual stars. The contours cover the range from 8 to 512 stars dmag\(^{-2}\), evenly spaced by factors of 2. This allows both the overall density distribution as well as the fine structure of the principal sequences to be shown in a single figure.

The main features that bear on the measurement of the star formation history, especially at the previously ill-constrained earliest times, are the relatively bright locations of the peak density of subgiants and the main-sequence turnoff; the underdeveloped horizontal branch and strong, vertically extended red clump; and the paucity of upper red giant branch stars. The implication of the bright subgiant branch is immediately evident by comparison to the location of the old, metal-poor isochrone in Figure 2:
have proven that for data of high quality, the details of the fitting procedure do not strongly affect the derived SFH (see also Skillman & Gallart 2002, Skillman et al. 2003, and A. Aparicio & S. L. Hidalgo 2007, in preparation).

The critical parameters \( m = M \), and \( E(B - V) \) were taken from the sources in Table 1. The solutions shown here were obtained using isochrones from Girardi et al. (2000) and the initial mass function from Chabrier (2003). Extinction in the ACS/WFC filter system was obtained by interpolation within the tables of Sirianni (2005): \( A_{434} = 0.033 \), \( A_{475} = 0.078 \).

We solved for the SFH in nine age bins; the age bins are logarithmically spaced to reflect the physical reality that the separation between isochrones of different ages is a strongly decreasing function of age. Within each age bin, a range of metallicities was allowed, from the lowest available metallicity to a value slightly higher than that corresponding to the van Zee et al. (2006) metallicity: \( 0.0001 \leq Z \leq 0.0015 \). The only constraint on age-metallicity relation was to exclude the lowest metallicity isochrones from the youngest age bins, as they are seen by inspection to be mismatched to the data. To restrict ourselves to inferences drawn from the best-modeled phases of stellar evolution, we use only the main-sequence and subgiant branch in our likelihood calculation. This does not significantly change the derived SFH because we include >90% of all stars; most of the excluded stars have very little age sensitivity, and their colors are strongly model-dependent.

Our derived history of star formation in Leo A is shown in Figure 3. The best-fit SFH is shown for two different age binnings (solid squares and open squares, respectively). Each point carries its \( 1 \sigma \) error bar in SFR and an age error bar marking the width of the age bin. The heavy curve is a cubic spline fit to the results; it represents our best estimate of the form of the SFH in the central part of Leo A. Because the total number of stars is fixed by the data, increasing the SFR in one age bin demands a decrease in the adjacent bin(s). Consequently, the error bars in Figure 3 imply that a slightly older, broader SFR peak is allowed by the data. The derived rates apply to the ACS/WFC field of view, which covers \( 0.6 \) kpc\(^2\) at a distance of 795 kpc; this is \( \approx 47\% \) of the area within the Holmberg radius and \( \approx 29\% \) of the area of Leo A’s intermediate-age disk (Vansevičius et al. 2004). The redshift scale at the top applies to a flat \( \Lambda \)CDM universe with parameters taken from the WMAP year-3 data set (Spergel et al. 2006). The stellar evolution and cosmological clocks disagree at early times because of missing physics in the stellar models. The most important of these is gravitational diffusion settling of light elements, which reduces the ages of low-mass stars by 10%–20% (Proffitt & VandenBerg 1991; Chaboyer et al. 1992).

Both solutions were obtained with fixed values of distance modulus, reddening, and binary star properties. We tested the sensitivity of the derived solution to reasonable variations in these parameters and found that for all reasonable parameter choices, the derived SFH has the same general form because of the exceptional photometric depth and completeness (A. A. Cole et al. 2007, in preparation). Leo A is best described as a late-blooming galaxy, in which the great majority of stars are formed after a delay of several gigayears. The apparent early peak of star formation above a subsequent minimum is not a high-confidence feature, as the error bars indicate.

The derived metallicity evolution is not plotted in Figure 3 because there is almost no trend with age. A constant heavy element mass fraction \( Z = 0.0008^{+0.0005}_{-0.0003} \) \((\text{Fe/H}) \approx -1.4 \pm 0.2\); ranges represent the rms scatter at a given age) is an adequate

14 Gyr old stars would produce a far fainter subgiant branch than observed. The peak density of subgiants occurs at \( M_{434} \approx +1.9 \), more than half a magnitude brighter than comparable measurements in globular clusters of similar metallicity (e.g., Rosenberg et al. 2000), but similar to intermediate-age clusters in the Small Magellanic Cloud (e.g., Mighell et al. 1998) and well matched to isochrones with ages \( \sim 5 \) Gyr. This is striking because a constant SFR produces a steep and monotonically increasing subgiant density with age (e.g., Gallart et al. 2005, Fig. 1). Because our photometry reaches the oldest main-sequence turnoff, we can unambiguously quantify the galaxy’s youth for the first time.

3. DERIVATION OF THE STAR FORMATION HISTORY

The quantitative star formation history of a stellar population can be derived from a CMD by comparison of the distribution of stars predicted by an ensemble of theoretical models, corrected for the effects of distance, interstellar reddening, and the completeness and precision limits imposed by the observations (e.g., Tolstoy & Saha 1996). The model predictions are derived from theoretical isochrones plus a prescription for the initial mass function from Chabrier (2003). Extinction in the ACS/WFC filter system was obtained by interpolation within the tables of Sirianni (2005): \( A_{434} = 0.033 \), \( A_{475} = 0.078 \). The critical parameters and were taken from Table 1. The solutions shown here were obtained using isochrones from Girardi et al. (2000) and the initial mass function from Chabrier (2003). Extinction in the ACS/WFC filter system was obtained by interpolation within the tables of Sirianni (2005): \( A_{434} = 0.033 \), \( A_{475} = 0.078 \). We solved for the SFH in nine age bins; the age bins are logarithmically spaced to reflect the physical reality that the separation between isochrones of different ages is a strongly decreasing function of age. Within each age bin, a range of metallicities was allowed, from the lowest available metallicity to a value slightly higher than that corresponding to the van Zee et al. (2006) metallicity: \( 0.0001 \leq Z \leq 0.0015 \). The only constraint on age-metallicity relation was to exclude the lowest metallicity isochrones from the youngest age bins, as they are seen by inspection to be mismatched to the data. To restrict ourselves to inferences drawn from the best-modeled phases of stellar evolution, we use only the main-sequence and subgiant branch in our likelihood calculation. This does not significantly change the derived SFH because we include >90% of all stars; most of the excluded stars have very little age sensitivity, and their colors are strongly model-dependent.

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representation of the results, although there is some hint of a trend of increasing metallicity with time, from $Z = 0.0006$ to $0.001$.

4. SUMMARY AND DISCUSSION

As suggested by Tolstoy et al. (1998) Leo A is a predominantly young galaxy. However, the depth of our photometry allows us to much more precisely describe its stellar age distribution; within the ACS/WFC field of view, 90% of the star formation has occurred more recently than 8 Gyr ago. The current star formation rate of $\approx 10^{-4} M_\odot$ yr$^{-1}$ is in good agreement with the rates estimated from H$\alpha$ emission. The large number of stars above the 5 Gyr isochrone shows that the SFR increased dramatically around this time and continued at high level for $\approx 3$ Gyr before declining. However, some truly ancient stars are required to reproduce the observed CMD and provide the observed RR Lyrae. The 14 Gyr isochrone in Figure 2 traces the lower envelope of subgiant stars, confirming that not all of the star formation was delayed.

Integrating over the radial profile from Vansevičius et al. (2004) we find that Leo A only strated $\approx (1-2) \times 10^6 M_\odot$ at ages corresponding to redshifts $z > 1$. If all of its present-day baryon inventory was present at high redshift, then Leo A would have been 95% gas and only 5% stars prior to $z \approx 2$. Although extreme, the $M(H_1)/L_\odot$ ratio of the young Leo A would have been comparable to those of the most gas-rich dwarf-irregular systems seen today (e.g., Warren et al. 2004). Evidently some small galaxies can retain or build large gas reservoirs without much depletion by star formation. This makes Leo A-like objects intriguing candidates for protogalactic fragments that merge into giant galaxies, disrupting bursts of star formation without leaving much stellar residue in their halos.

Because of uncertainties in assigning absolute ages to old stellar populations, and because our time resolution decreases with age, we cannot rule out that all of the ancient star formation in Leo A took place prior to reionization. That would require compressing all of the ancient star formation in Figure 3, plus the formation of the unobserved Population III stars that enriched the galaxy to its "initial" metallicity [Fe/H] $\approx -1.5$, into an $\sim 0.5$ Gyr window.

Leo A is not the only "late bloomer" in the Local Group, but it appears to be an extreme case. An example of a qualitatively similar SFH can be found in the Leo I (Gallart et al. 1999) dwarf spheroidal (dSph) galaxy. The two galaxies are of comparable mass, but the latter is a gas-free, bound satellite of the Milky Way, with plausible triggers for late star formation in tidal interactions or accretion events. A trigger in the case of Leo A is harder to identify.

The idea that a dwarf galaxy’s SFR is tied only to the gas infall rate would require an unusual merger history for this tiny, isolated system. Leo A would have gained virtually all of its gas in the past few gigayears: not enough time for it to have reached its present remote location from the vicinity of M31 or the Milky Way, where encounters might be expected to be more likely. Given its probable long history of isolation, it may be that much of the gas in Leo A was present from early on, and therefore the suppression of early star formation is not attributable to the loss or exhaustion of its initial reservoir. It seems more plausible that only a small fraction of the H$\alpha$ was able to participate in star formation, with the rest kept warm in a halo; the UV background or supernova feedback are candidate heat sources. Sequestering most of the gas in a halo also speeds the chemical evolution clock, which is interesting given the prompt enrichment and subsequent flat age-metallicity relation in the galaxy. The warm halo would have been diffuse and metal-poor, resulting in a long cooling timescale and a possible delay before it could participate in star formation—perhaps triggered by a rare infall or interaction event in this isolated dwarf.

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