The pulsating variable star population in DDO210

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ABSTRACT
We have probed the pulsating variable star content of the isolated Local Group dwarf galaxy, DDO210 (Aquarius), using archival Advanced Camera for Surveys/Hubble Space Telescope imaging in the F475W and F814W passbands. We find a total of 32 RR Lyrae stars (24 ab-type; 8 c-type) and 75 Cepheid variables. The mean periods of the ab-type and c-type RR Lyrae stars are calculated to be $\langle P_{ab} \rangle = 0.609 \pm 0.011$ and $\langle P_c \rangle = 0.359 \pm 0.025$ days, respectively. The light curve properties of the fundamental mode RR Lyrae stars yield a mean metallicity of $\langle [\text{Fe/H}] \rangle = -1.63 \pm 0.11$ dex for this ancient population, consistent with a recent synthetic colour-magnitude diagram analysis. We find this galaxy to be Oosterhoff-intermediate and lacking in high-amplitude, short-period ab-type RR Lyrae, consistent with behavior recently observed for many dwarf spheroidals and ultra-faint dwarfs in the Local Group. We find a distance modulus of $\mu = 25.07 \pm 0.12$ as determined by the RR Lyrae stars, slightly larger but agreeing with recent distance estimates from the red giant branch tip. We also find a sizable population of Cepheid variables in this galaxy. We provide evidence in favor of most if not all of these stars being short-period classical Cepheids. Assuming all of these stars to be classical Cepheids, we find that most of these Cepheids are $\sim$300 Myr old, with the youngest Cepheids being offset from the older Cepheids and the centre of the galaxy. We conclude that this may have resulted from a migration of star formation in DDO210.

Key words: galaxies: Dwarf – galaxies: individual: DDO210 – stars: abundances – stars: variables: RR Lyrae – stars: variables: Cepheids

1 INTRODUCTION
Dwarf galaxies are known to be the most numerous type of galaxy in general. Additionally, dwarf galaxy accretion has been proposed as one of the major mechanisms in the formation of massive galaxies, such as the Milky Way (MW) (Mateo 1998). While the notion of MW halo build-up from systems resembling modern day dwarf spheroidals (dSph) has encountered significant contention recently from element abundance ratio comparisons with the Galaxy (Venn et al. 2004; Pritzl, Venn, & Irwin 2005) and the Oosterhoff dichotomy (Catelan 2009), accretion of dwarfs has certainly occurred, with the Sagittarius dSph providing a smoking gun for such interactions (Ibata, Gilmore, & Irwin 1994). Studying the stellar populations of Local Group (LG) dwarfs, especially the old ones, allows us to better constrain the extent to which these dwarfs have contributed to the Galactic halo. Dwarf galaxies also present unique astrophysical laboratories to study how these relatively simple galaxies have evolved in different environments through their chemical enrichment and star formation histories (SFHs).

Variable stars are important tracers of the histories of dwarf galaxies. They provide unique insights into their parental stellar populations through the study of their light curves. Cepheid and RR Lyrae variables are especially useful in this context. For instance, classical Cepheids (CCs) are massive, blue-loop stars that are relatively young, having formed within the past $\sim$1 Gyr (Bono et al. 2005). Therefore these stars trace young star formation events. On the other hand, RR Lyrae stars are ancient horizontal branch (HB) stars originating from low-mass stars, and thus trace star formation at ages $\geq$10 Gyr (see Figs. 2 and 3 of Lee, Demarque, & Zinn 1994 for theoretical modeling of RR Lyrae stars on the HB and Glatt et al. 2008 for an age determination of the youngest known system harboring RR Lyrae stars). Anomalous Cepheids (ACs) are thought to represent more intermediate-mass stars at low metallicities. They may trace intermediate age (1-6 Gyr) populations or old binary systems (Fiorentino & Monelli 2012). The mere presence of any combination of these stars thus provides constraints on the SFH of the host system.

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In addition to informing the SFH of a stellar population, pulsating variables also provide insight into the chemical enrichment of such a population. Most notably, there are strong correlations between the light curve shapes of fundamental mode RR Lyrae, referred to in the literature as RRab stars, and their iron abundances, [Fe/H] (Jurcsik & Kovács 1996; Alcock et al. 2000; Nemec et al. 2013). Similar relationships for Cepheids have recently been explored (Szabados et al. 2012; Klagyivik et al. 2013). Therefore, these stars provide a means to elucidate portions of the chemical enrichment history of a stellar population without the need for spectroscopic observations.

The LG dSph/Irr transition-type (dTrans; see Mateo 1998) galaxy, DDO210 (Aquarius), is one of the most distant dwarf galaxies in the LG. While distance estimates to this galaxy have differed significantly over the past few decades, recent values have converged on a distance of $d \sim 1$ Mpc using the tip of the red giant branch (TRGB) (Cole et al. 2014). This galaxy is one of the most isolated in the LG and thus provides an excellent opportunity to study how such low-mass, isolated dwarfs evolve.

Recently Cole et al. (2014) presented a synthetic colour-magnitude diagram (CMD) analysis of the SFH of DDO210 using their Hubble Space Telescope (HST)/Advanced Camera for Surveys (ACS) observations (GO-12925; PI: A. Cole). They find a complex SFH over the lifetime of DDO210 characterized by a long delay before the onset of a major starburst. In this paper, we use their analysis to study how such short-period variable stars within the context of the SFH of DDO210 is given in Section 3.1 and the conclusions are presented in Section 4.

2 OBSERVATIONS AND DATA REDUCTION

The data set used by Cole et al. (2014) is very deep and covers a time baseline conducive to identifying short-period variable stars. These observations of DDO210 were originally intended for use in a detailed SFH analysis for this dwarf, and thus cover a significant portion of the galaxy while reaching photometric depths to the main-sequence turnoff. The observations consisting of 22,920 seconds in F475W and 33,480 seconds in F814W were taken with a cadence well-suited for identifying short-period variable stars. We retrieved these images from the Mikulski Archive for Space Telescopes (MAST) for use in our study.

We downloaded the charge-transfer efficiency (CTE) corrected (+FLC) images from MAST, which were also processed through the standard HST pipeline. Bad pixels were then masked and the geometric correction pixel area maps were applied to each image. Photometry was then performed using the DAOPHOT/ALLSTAR/ALLFRAME software packages (Stetson 1987; 1994). Empirical point-spread functions (PSFs) were constructed using the brightest isolated stars in one cosmic-ray rejected reference image for each filter using the corresponding task in DAOPHOT. Aperture corrections were calculated from bright, isolated stars on each chip. The median aperture correction for these stars was then applied to all stars. We noticed a small photometric offset between the WFC1 and WFC2 chips after the aperture correction, and placed the WFC2 photometry on the same scale as the WFC1 photometry for consistency. The data set used by Cole et al. (2014), who used the same data set, revealed that the WFC1 photometry agreed with theirs. We attribute this error to the lack of bright, isolated stars in the WFC2 field with which to obtain an accurate aperture correction value. Finally, conversion of the native HST VEGAMAG photometry to the ground-based Johnson-Cousins B and I filters was accomplished using the prescription from Sirianni et al. (2005).

3 VARIABLE STAR CHARACTERIZATION AND SIMULATIONS

3.1 Characterization

In order to identify potential variable stars within the photometry, we first applied cuts in magnitude and colour in order to narrow our region of interest. Since the primary goal of this work is to characterize the pulsating variable stars within the instability strip, we determined stars within 21 mag $< m_{FB814W} < 27$ mag and $< m_{FB475W} - m_{FB814W} < 1.5$ mag to be an appropriate region of interest. Potential variable stars were identified using a reduced $\chi^2$ defined as:

$$\chi^2 = \frac{1}{N_1 + N_2} \times \left[ \sum_{i=1}^{N_1} \frac{(m_{i,1} - \bar{m_1})^2}{\sigma_i^2} + \sum_{i=1}^{N_2} \frac{(m_{i,2} - \bar{m_2})^2}{\sigma_i^2} \right]$$

(1)

In this case, $m_1$ and $m_2$ are the F475W and F814W magnitudes in the VEGAMAG photometric system. In an effort to filter spurious variables, we rejected 3-$\sigma$ outliers from the $\chi^2$ calculation for each light curve. Stars with $\chi^2 \geq 2$ were flagged as variable candidates.

The raw light curve of one of the variable candidates is shown in Fig. 1. This light curve illustrates the high quality of these data for identifying variable stars. Table 2 provides the full, time-series photometry for this star, and the photometry for all variable candidates is available in the online version of this study.

Once we identified our set of variable candidates, we then removed data points from each light curve with anomalously high errors ($\geq 0.1$ mag) to ensure a final sample of high fidelity light curves. Analysis of these light curves was then performed using template light curve fitting. This method, based largely off the technique originated by Layden et al. (1999), caters well to data sets with sparse or irregular time sampling and large gaps. We use RRFIT (Yang &
We then ran a second round of RRFIT on each set of variable candidates, this time tailoring the pulsational parameter space to match each type of variable. In the case of the Cepheid candidates, we searched for periods in the range of 0.2–1.0 days, covering the period distributions for the different subclasses of Cepheids found in LG dwarf galaxies. We chose to use the RR Lyrae templates for the Cepheids since the light curve shapes are similar. For the RR Lyrae candidates, we searched for periods in the usual range of 0.4–4.0 days.

We took advantage of the relationship between pulsation amplitudes in different bandpasses for the RR Lyrae stars as discussed in Dorfi & Feuchtinger (1999) in order to improve the template fitting procedure for these stars. Dorfi & Feuchtinger (1999) provide these relationships in the Johnson–Cousins system for the B, V, and I filters. In order to derive similar transformations for the VEGAMAG photometric system, we used the following technique. First, we generated 4,000 artificial RR Lyrae light curves using the templates in RRFIT. These artificial light curves were generated with the following constraint on their amplitudes from Dorf & Feuchtinger (1999). We then ran a second round of RRFIT performs a robust search through the user defined parameter space of expected pulsational properties to find the best-fitting light curve template for each star. The program does so by thoroughly searching the defined period space and generating potential light curves based upon the supplied templates at each period using the genetic algorithm, PIKAIA (Charbonneau 1995), to optimize each template to fit the data. Each light curve fit is then ranked according to its reduced $\chi^2$, and the parameters that minimize this value are taken to be the best-fitting light curve.

Given previous studies of the stellar populations and SFH in DDO210, we expect there to be a sizable population of RR Lyrae variables as well as Cepheid variables. Considering this, we performed a first-pass with RRFIT on our entire set of variable candidates searching for periods in the range 0.2–1.0 days. Following this, we performed a first-pass with RRFIT on our entire set of variable candidates searching for periods in the range 0.2–1.0 days. Following this, we performed a first-pass with RRFIT on our entire set of variable candidates searching for periods in the range 0.2–1.0 days. Following this, we performed a first-pass with RRFIT on our entire set of variable candidates searching for periods in the range 0.2–1.0 days. Following this, we performed a first-pass with RRFIT on our entire set of variable candidates searching for periods in the range 0.2–1.0 days.
We then transformed these light curves to the VEGAMAG magnitudes in F475W and F814W using the prescription from Sirianni et al. (2005) at each phase in the light curve. Finally, the amplitudes in F475W and F814W were calculated for each synthetic light curve, and the following linear relation was fit to these amplitudes:

$$A_{F475W} = 0.089 + 1.734A_{F814W}$$  \hspace{1cm} (3)

Equation (3) thus provides a constraint on the amplitudes of the RR Lyrae candidates in the VEGAMAG photometric system. We modified RRFIT to implement this constraint in order to improve the accuracy of the RR Lyrae fitting routine. On the other hand, for Cepheids it has been known for some time that the amplitude ratio $A_B/A_V = 0.6$ mag is independent of period or amplitude (Tanvir 1997). However, the findings of Coulson & Caldwell (1989) suggest a possible dependence of $A_B/A_V$ on period, so we did not implement any such amplitude constraint on the Cepheid candidates.

Finally, we performed multiple checks on these best-fitting light curve to assess their validity. For the RR Lyrae stars, the locations in the Bailey (period-amplitude) diagram was checked to verify that each light curve’s period, amplitude, and mode follow the well-known behavior of RR Lyrae stars in this space. We manually checked for potential aliasing by visually examining all light curves produced by RRFIT. Light curves with periods suspected to be aliased were checked with the interactive light curve fitting program, FITLC (Mancone & Sarajedini 2008). This software operates on the same principles as RRFIT but provides a GUI for the user to examine the light curves and the period-$\chi^2$ space. This program illustrates the best-fitting light curve for each template overplotted on the data, along with a plot of reduced $\chi^2$ versus period for each template. In this way, FITLC allows one to explore different period/template combinations. Occasionally, the automated fitting routine misclassifies a star or falls victim to a period alias. Aliased periods can be compared with other periods lying at a similar $\chi^2$ minimum. If a fit appears anomalous on the Bailey diagram (e.g. significantly shorter/longer period at a given amplitude compared with the other RR Lyrae stars on the diagram), or a period-folded light curve appears to have a large gap, the fit period is usually aliased with two or more comparable $\chi^2$ minima. Using FITLC, we explored the different periods with similarly low $\chi^2$ for these problematic light curves. If one of these other periods yields light curve parameters that better match the data and/or previously observed behavior for that type of variable (e.g. period-amplitude relation), then that period is taken as the correct one. We will hereafter refer to this procedure as manual fitting.

Stars which failed to pass this vetting procedure with reasonable properties were removed from the sample. This left 107 (75 Cepheid; 32 RR Lyrae) high confidence variable stars in our sample. Manual fitting with FITLC was required for 4 RR Lyrae stars and 7 Cepheids, accounting for 10% of our total pulsating variable sample. The CMD locations of our final variable star sample are shown in Fig. 2. Some example light curves of each of these variables, folded with the best-fitting period, are plotted in Figs. 3 and 4. Properties of each of these candidate pulsators are presented in Table 2.

### 3.2 Simulations

We performed artificial light curve simulations to assess the accuracy and precision of our automated fitting procedure on this data set (see Ordoñez, Yang, & Sarajedini (2014) and references therein). This involved using the Fourier templates from RRFIT to create artificial light curves. The properties of these artificial light curves were chosen to best represent the types of pulsating variables found in DDO210. We sampled the appropriate period, amplitude, magnitude, and colour ranges in which the RR Lyrae and Cepheids were found to lie. Each of these properties was sampled from a uniform distribution and assigned to each individual light curve. For the artificial RR Lyrae light curves, the amplitude constraint in Equation (3) was applied. Observations on these artificial F475W,F814W light curves were then simulated utilizing the cadence of our dataset and realistic photometric errors.

Unlike the other studies employing these artificial light curve simulations, we have accounted for ranges in magnitude and colour, utilizing the photometric errors as a func-
Figure 3. Example light curves of some Cepheid variables in DDO210. Open circles represent F814W observations, while filled circles are F475W observations. The solid lines illustrate the best-fitting templates to each light curve.
Figure 4. Same as Fig. 3 for some RR Lyrae variables.
Table 2. Properties of the pulsating variables in DDO210.

| Star ID | RA (J2000) | Dec (J2000) | Type     | Period (days) | $A_B$ (mag) | $A_I$ (mag) | $\langle B \rangle$ (mag) | $\langle I \rangle$ (mag) | $\langle B-I \rangle$ (mag) |
|---------|-------------|-------------|----------|--------------|-------------|-------------|-----------------|-----------------|-----------------|
| V0074   | 20 46 17.2113 | -12 55 35.626 | RRab     | 0.394        | 0.390        | 0.253        | 24.901           | 23.014           | 1.887           |
| V0075   | 20 46 17.32704 | -12 55 37.054 | RRab     | 0.322        | 0.315        | 0.183        | 24.976           | 23.071           | 1.905           |
| V0076   | 20 46 17.3308 | -12 55 38.1836 | RRab     | 0.454        | 0.451        | 0.305        | 24.804           | 23.023           | 1.781           |
| V0077   | 20 46 17.7346 | -12 55 38.8416 | RRab     | 0.732        | 0.735        | 0.460        | 24.056           | 23.207           | 0.849           |
| V0080   | 20 46 17.8368 | -12 55 39.0075 | RRab     | 0.560        | 0.561        | 0.350        | 24.976           | 23.106           | 1.870           |
| V0081   | 20 46 17.8382 | -12 55 39.1495 | RRab     | 0.640        | 0.641        | 0.449        | 24.118           | 23.259           | 0.860           |
| V0082   | 20 46 17.9362 | -12 55 39.5766 | RRab     | 0.732        | 0.735        | 0.460        | 24.056           | 23.207           | 0.849           |
| V0083   | 20 46 18.4920 | -12 55 40.0276 | RRab     | 0.673        | 0.727        | 0.497        | 24.222           | 23.369           | 0.853           |
| V0084   | 20 46 18.5884 | -12 55 40.5521 | RRab     | 0.576        | 0.579        | 0.320        | 25.017           | 23.462           | 1.655           |
| V0085   | 20 46 18.5954 | -12 55 40.5916 | RRab     | 0.629        | 0.765        | 0.496        | 24.194           | 23.094           | 0.999           |
| V0086   | 20 46 18.6375 | -12 55 40.8757 | RRab     | 0.634        | 0.682        | 0.408        | 25.073           | 23.569           | 1.504           |
| V0087   | 20 46 18.6425 | -12 55 41.0367 | RRab     | 0.649        | 0.794        | 0.472        | 25.170           | 23.630           | 1.540           |
| V0088   | 20 46 18.6443 | -12 55 41.0961 | RRab     | 0.467        | 0.608        | 0.394        | 25.017           | 23.462           | 1.655           |
| V0089   | 20 46 18.6482 | -12 55 41.1381 | RRab     | 0.526        | 0.677        | 0.435        | 25.017           | 23.462           | 1.655           |
| V0090   | 20 46 18.6586 | -12 55 41.2878 | RRab     | 0.576        | 0.682        | 0.408        | 25.073           | 23.569           | 1.504           |
| V0091   | 20 46 18.6611 | -12 55 41.3161 | RRab     | 0.673        | 0.727        | 0.497        | 24.222           | 23.369           | 0.853           |
| V0092   | 20 46 18.6621 | -12 55 41.3716 | RRab     | 0.576        | 0.682        | 0.408        | 25.073           | 23.569           | 1.504           |
| V0093   | 20 46 18.6686 | -12 55 41.4316 | RRab     | 0.576        | 0.682        | 0.408        | 25.073           | 23.569           | 1.504           |
| V0094   | 20 46 18.6706 | -12 55 41.4956 | RRab     | 0.649        | 0.794        | 0.472        | 25.170           | 23.630           | 1.540           |
| V0095   | 20 46 18.6716 | -12 55 41.5266 | RRab     | 0.467        | 0.608        | 0.394        | 25.017           | 23.462           | 1.655           |
| V0096   | 20 46 18.7176 | -12 55 41.7756 | RRab     | 0.526        | 0.677        | 0.435        | 25.017           | 23.462           | 1.655           |
| V0097   | 20 46 18.7218 | -12 55 41.8956 | RRab     | 0.576        | 0.682        | 0.408        | 25.073           | 23.569           | 1.504           |
| V0098   | 20 46 18.7218 | -12 55 41.8956 | RRab     | 0.673        | 0.727        | 0.497        | 24.222           | 23.369           | 0.853           |
| V0099   | 20 46 18.7257 | -12 55 41.9823 | RRab     | 0.576        | 0.682        | 0.408        | 25.073           | 23.569           | 1.504           |

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tion of magnitude in each the F475W and F814W bands. We modeled the photometric error function as a constant value for bright magnitudes, and an exponential function for fainter magnitudes. This model was then fit to the errors from each individual photometric measurement for every star in our sample. In this way, we were able to realistically assess how our light curve analysis accuracy and completeness vary as a function of magnitude.

Once the simulated observations were generated, we then input these into RRFIT exactly as we did for our real light curves. The difference between the synthetic input and best-fitting light curve parameters for each artificial light curve then gives estimates of the uncertainties inherent in the fitting procedure. We show the results of these simulations for the Cepheid, RRab, and RRc stars in Fig. 5.

Given that these data cover a baseline of ~2.5 days, it is expected that periods greater than this to be recovered with significantly less accuracy than for shorter periods. This is clearly visible in the Cepheid simulations. However, for periods shorter than 2.5 days, the period errors remain constant and reasonably small. Only 3 of the 75 Cepheid candidates were fit with periods longer than 2.5 days, and the longest period Cepheid (5.15 days) was fit manually in FITLC since it fell outside of the explored period range. Therefore, we expect the observing baseline to affect the periods of only 2 out of the 107 variables in our sample.

To gauge the quantitative uncertainties inherent in the fitting routine from these simulations, we perform the following statistical test discussed in Ordoñez et al. (2014). From our sample of artificial light curves, we sample the corresponding number of identified stars (75 Cepheid; 24 RRab; 8 RRc) and calculate the average error in the light curve parameters (ΔP, ΔF475W, etc.). This sampling is repeated 10,000 times to build a statistical distribution of the expected errors. These distributions then represent good estimators for the systematic and random errors inherent in the fitting procedure. Specifically, the peak of the distribution reveals any systematic errors, and the spread estimates the random uncertainties (standard error) in each parameter. Gaussian fits to the final error distributions therefore yield our fiducial uncertainty values. These uncertainties are presented in Table 3 for each type of simulated variable. Since only 2 Cepheids will be affected by the large uncertainties at P>2.5 days, we restricted this test to artificial light curves with periods less than this value.

We conclude this section by pointing out that for most of the simulated light curve parameters, the systematic errors are smaller than the random errors. However, the simulations reveal that we may be underestimating the amplitudes for the Cepheid and RRab light curves by 0.02 and 0.04 mag, respectively. We tested to see if this affected the metallicity estimates for the RRab stars (see Section 4.1) by subtracting this offset from the amplitudes, and it turned out to drive the metallicity estimates higher by ~0.05 dex. Considering that this is smaller than the other sources of uncertainty for this calculation, we do not expect these errors to impact the main results of this paper significantly.

4 RR LYRAE STARS

The relative paucity of RR Lyrae stars in DDO210, especially compared with the younger Cepheids, is fully consistent with the appearance of its CMD. The red HB morphology and strong red clump (RC) in this galaxy indicate a younger average age for the stellar population. The small number of RR Lyrae stars implies a weaker star formation rate at times ≥10 Gyr ago, which is fully consistent with the appearance of the other features. This agrees well with the synthetic CMD, SFH analysis of Cole et al. (2014). Their Fig. 4 shows a distinct minimum just before a lookback time of 10 Gyr.

4.1 Metallicity of RRab stars

In addition to providing insights into the SFH of a galaxy, the RR Lyrae stars also inform us regarding the chemical enrichment of their host system through their metallicity distribution function (MDF). As discussed in Section 4.1, many studies have provided methods of calculating an iron abundance, [Fe/H], from the shape of the light curves of RR Lyrae stars. Considering that the dataset employed in this study is not well-suited for a Fourier analysis on each light curve, we utilized the relation of Alcock et al. (2000) to calculate [Fe/H] for each individual RRab star:

\[ [\text{Fe/H}] = -8.85\log P\, \text{ab} + 0.15A_V - 2.60 \]  (4)

Since we did not have V band imaging for these stars, we opted to estimate \( A_V \) for each RRab star using the relation between \( A_B \) and \( A_V \) from Dolfi & Feuchtiger (1999).

Fig. 5 shows the RRab MDF calculated using both the I-band and B-band amplitudes. The MDFs show no significant difference, and the mean metallicity in each case is \((\langle [\text{Fe/H}] \rangle = -1.65 \pm 0.11 \text{ dex using } A_I \) and \((\langle [\text{Fe/H}] \rangle = -1.61 \pm 0.11 \text{ dex using } A_B \), both in full agreement. We thus take a singular estimate by averaging these two values together to obtain \((\langle [\text{Fe/H}] \rangle = -1.63 \pm 0.11 \text{ dex}. Assuming the effects of α-enhancement are small, this also agrees with the AMR from the synthetic CMD analysis of Cole et al. (2014). Their Fig. 5 shows this AMR, and at a lookback time of approximately 11 Gyr, this average metallicity is \([\text{M/H}] \sim -1.7 \text{ dex}. The RRab stars, which formed at approximately this time, support the results of the analysis of Cole et al. (2014).

4.2 Bailey diagram

An important diagnostic of an RR Lyrae population is the Bailey (period-amplitude) diagram. We show this for the 32 RR Lyrae stars within DDO210 in Fig. 7. Also plotted in this figure are the loci for the two different Oosterhoff populations in the Galactic globular clusters (GGCs) from Cacciari, Corwin, & Carney (2005). While most of the RRab stars lie around the Oosterhoff type I (OoI) locus, their mean period \( \langle P \rangle = 0.690 \pm 0.011 \text{ d} \) and mean metallicity \( \langle [\text{Fe/H}] \rangle = -1.63 \pm 0.11 \text{ dex place this galaxy in the so-called Oosterhoff gap, along with the majority of dSph galaxies. Additionally, the first-overtone to fundamental mode population ratio, (RRc)/(RRc + RRab) = 0.25, is consistent with an Oosterhoff-intermediate classification for this galaxy.}

The discrepancy between the appearance of the Bailey diagram and the other Oosterhoff classification methods
Figure 5. Results of the light curve simulations. The left panels show the period error as a function of input period, while the right panels show the amplitude error versus input F475W amplitude.
Table 3. Uncertainties estimated from the light curve simulations.

| Variable | $\sigma_{\text{systematic}}$ (d) | $\sigma_{\text{random}}$ (d) | $\sigma_{\text{AF475W systematic}}$ (mag) | $\sigma_{\text{AF475W random}}$ (mag) | $\sigma_{\text{AF475W systematic}}$ (mag) | $\sigma_{\text{AF475W random}}$ (mag) |
|----------|-------------------------------|-----------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Cepheid  | -0.0444                       | 0.0058                      | -0.0233                         | 0.0103                          | -0.0004                         | 0.0043                          |
| RRab     | -0.0011                       | 0.0042                      | -0.0399                         | 0.0257                          | 0.0049                          | 0.0103                          |
| RRc      | 0.0007                        | 0.0026                      | -0.0213                         | 0.0228                          | -0.0022                         | 0.0073                          |

Figure 6. The MDF of the RRab stars using the relation of Alcock et al. (2000) to calculate the metallicities. The solid line represents the MDF calculated converting $A_I$ to $A_V$. The dashed line is the same but estimating $A_V$ from $A_B$.

Figure 7. The Bailey diagram for the RR Lyrae stars in DDO210. RRab stars are represented as filled circles, while the open triangle represent the RRc stars. Plotted as the solid and dashed lines are the Oosterhoff I and II trend lines from Cacciari et al. (2000).

have been noted in previous studies (Ordoñez et al. 2014; Stetson 2014; Fiorentino et al. 2015). This paper discusses this issue in detail, and concludes that the absence of high-amplitude, short-period (HASP) RRab stars in dSph and ultra-faint dwarf (UFD) galaxies presents a fundamental difference between the ancient RR Lyrae population in dSph/UFDs and those in the GGCs and Galactic Halo. This HASP absence, which Fiorentino et al. (2015) attribute to the metal-poor environments forming the RR Lyrae stars, skews the mean RRab period to longer values. Therefore, it seems that DDO210 hosts an RR Lyrae population similar to the dSph and UFDs in the LG owing to their similarly metal-poor environments at early ages.

4.3 Distance to RRab stars

The distance to DDO210 has been a matter of some debate since its discovery. Most recent distance estimates to this galaxy using the TRGB place DDO210 at a distance modulus of $\mu \sim 25$ (McConnachie et al. 2005; Jacobs et al. 2009), and the most recent synthetic CMD analysis by Cole et al. (2011) report a distance modulus of $\mu = 24.95 \pm 0.10$. We now compute the distance to DDO210 using the period-luminosity-metallicity (PLZ) relation from Catelan et al. (2004).

$$M_I = 0.471 - 1.132\log P + 0.205\log Z$$

Using the RRab metallicities from Section 4.1 calculated with the $I$-band amplitudes, we convert to $\log Z$ using the following relation: $\log Z = [Fe/H] - 1.765$ to remain consistent with Catelan et al. (2004). Again, here we have not corrected for the effects of $\alpha$-enhancement in the absence of a strong constraint for [$\alpha$/Fe] for these stars. Apparent mean magnitudes of these RRab stars have been corrected for extinction using $A_I = 0.076$ mag from Schlafly & Finkbeiner (2011) for DDO210 retrieved from NED.

The mean distance modulus of the RRab stars calculated in this way is $\mu = 25.07 \pm 0.12$ where the error bar represents one standard deviation. We note that the effects of different helium abundances on this RR Lyrae PLZ relation have not been fully explored, and significant helium abundance in the DDO210 RR Lyrae stars could present a significant systematic error in this distance determination. There may also be some systematic error resulting from $\alpha$-enhancement when calculating $\log Z$. Even considering these uncertainties, our RR Lyrae distance is roughly consistent with other distance determinations to this galaxy within the uncertainties. The RR Lyrae distance does however seem to lie on the farther end of the distribution of previous distance measurements. In fact, our distance is closer to that of McConnachie et al. (2005) ($\mu = 25.15 \pm 0.08$).

https://ned.ipac.caltech.edu/
4.4 Peculiar RR Lyrae candidates

We now turn to discussing a few anomalous RR Lyrae candidates within our sample. The CMD of DDO210 in Fig. 2 shows two bright outliers in the RR Lyrae population near $m_{F475W} = 25.4$ mag and colours of $(F475W - F814W) = 0.6$ and $(F475W - F814W) = 0.8$ mag. Neither of these RRab stars appear as outliers in the Bailey diagram, nor do they display anomalous light curves. It is evident from Fig. 2 that most of the RR Lyrae candidates that we identified occupy the expected region in the CMD, except for the two aforementioned bright outliers lie clearly brighter the HB. In fact, these stars appear to lie in between the bulk RR Lyrae population and the Cepheids. It is possible that these stars are faint ACs, but this seems unlikely given their separation from the bulk Cepheid population in the CMD and PL relations (see Section 5 for a full discussion of the Cepheids).

We also considered the possibility that these stars are type II Cepheids (BL Her) stars, but ruled this out because BL Her stars generally have periods between 1 and 4 days (these outliers both have periods near 0.4 days). Another possibility is that these stars contain unresolved companions, making them appear brighter. This is more likely the case as Cepheids with such short periods are uncommon.

One more peculiar RR Lyrae candidate deserves discussion. Immediately apparent upon examining Fig. 7 is the one outlying RRab star near the OoII locus. The longest period RR Lyrae in our sample, this star is also the most metal-poor RRab star. While it is tempting to discard this star as a contaminating Type II or anomalous Cepheid, we note that this star lies right on the HB ($m_{F475W} = 25.91$ mag) in the CMD near the red end of the RR Lyrae gap. It may therefore be a very metal-poor RR Lyrae star formed within DDO210. Considering once again the analysis ofCole et al. (2014) for comparison, we see that the AMR for the galaxy has the largest metallicity dispersion at a lookback time of 11 Gyr, corresponding to the age of the RR Lyrae stars. In fact, the rms metallicity range for that time bin extends down to metallicities of $[M/H] = -2.5$ dex. Therefore, such a metal-poor RR Lyrae star is not inconsistent with the synthetic CMD analysis ofCole et al. (2014).

5 CEPHEIDS: ANOMALOUS OR CLASSICAL?

5.1 Comparison with evolutionary tracks

The Cepheid variables dominate the pulsators found in DDO210. However, as other authors have pointed out (Fiorentino et al. 2012), this region of the CMD hosting these stars is degenerate. That is to say that stellar populations with different masses and metallicities can occupy this region, including the Cepheid instability strip. In low-metallicity environments, this makes distinction between these different populations difficult. We note that no Cepheids with periods longer than $\sim 5$ days were identified in our data. Given the quality of the data at these bright magnitudes, we expect to flag variability at these longer periods even with incomplete phase coverage. Therefore, this absence of longer period Cepheids is more likely a reflection of the Cepheid population itself rather than an observational bias.

To further complicate matters, recent investigations of the Cepheid populations in dwarf galaxies have revealed that the distinction between ACs and CCs is not as clear as one might think. These studies have found that the period and luminosity distributions of these two types of variables can overlap, making a separation based on this diagram alone difficult (Gallart et al. 2004; Fiorentino et al. 2012; Clementini et al. 2012; Bernard et al. 2013; Stetson 2014). One other way to potentially distinguish between a population of CCs and ACs is to utilize our theoretical understanding of ACs. Since ACs are stars with masses less than the transition mass between partial-degenerate, central He burning and quiescent central He burning, one can compare the positions of stellar evolutionary tracks near this mass ($\sim 1.3 M_{\odot}$ for $[Fe/H] \leq 0.7$ dex) with the observed Cepheid population (Fiorentino et al. 2012).

We have performed this analysis for the Cepheids in DDO210, and the results are shown in Fig. 8. This shows the CMD of DDO210 highlighting the Cepheid variables. The magnitudes have been converted to absolute magnitudes using the RR Lyrae distance modulus and reddening-free, Wesenheit PL relations in Fig. 9. Again, for ages $\leq 6$ Gyr, it is evident that the brighter Cepheids in this galaxy are clearly CCs, irrespective of the metallicity adopted for these stars. We have identified these stars as lying near or brighter than the 2.8 $M_{\odot}$ track in both cases (the triangles in Fig. 8). The remaining Cepheids cluster around the 2.1 $M_{\odot}$ track for the lower metallicity case but not the higher metallicity case. Thus, we are presented with a situation similar to what Fiorentino et al. (2012) found in Leo I. That is, the nature of the Cepheids in DDO210 seems to depend on the metallicity of these stars. If they are sufficiently metal-poor, which Kirby et al. (2013) indicate is possible calculating $[Fe/H] = -1.44$ dex for DDO210, it is likely that many of the fainter Cepheids are ACs. On the other hand, if these stars are all characterized by a slightly higher metallicity, as is suggested by the AMR of Cole et al. (2014) for ages $\leq 6$ Gyr, then these Cepheids should all be CCs.

5.2 PL relations

The locations of these stars in the CMD coupled with the AMR from Cole et al. (2014) indicate that most if not all of these stars are in fact CCs. In an attempt to place further constraints on the nature of these Cepheids, we show the $M_B$ and reddening-free, Wesenheit PL relations in Fig. 9. Again, we have used the RR Lyrae distance modulus and extinctions as before to convert to absolute magnitudes. We have
taken several PL relations from the literature for CCs and ACs to compare with the Cepheids in DDO210. For the CCs, we use the $B$-band PL relation from Gallart et al. (2004) for short-period CCs. As for the ACs, we use the $B$-band PL relation from Pritzl et al. (2002). Although there is a considerable amount of scatter, it appears that the likely CCs identified using Fig. 8 (triangles in Fig. 9) see Section 5.1 do follow the CC PL relations. As for the fainter Cepheids, the picture is again unclear. The faintest of these do seem to aggregate near the AC PL relations, but there is enough scatter to confuse the distinction for most of them.

The Wesenheit magnitudes inherently remove the effects of reddening to stars (Brodie & Madore 1980). To calculate Wesenheit magnitudes, we use the following equation:

$$W_B = M_B - R(B - I)_0$$

Here, $R$ is the ratio of total-to-selective absorption, $A_B/E(B-I) = 1.710$ (Schlafly & Finkbeiner 2011). We have constructed $W_B$ PL relations using the $B$-band PL relations previously mentioned combined with the $I$-band relations of Fiorentino et al. (2006) for the ACs, Udalski et al. (1999) for the fundamental mode CCs, and Soszynski et al. (2008) for the first-overtone CCs. We note that we needed to place the first-overtone CC PL relation on the same scale as the fundamental mode one by subtracting 18.449 mag from the first-overtone CC PL relation of Soszynski et al. (2008). This was necessary because this PL relation was not corrected for reddening, but Udalski et al. (1999) did not provide a first-overtone PL relation. Thus, subtracting the difference between the fundamental mode zero-points of Soszynski et al. (2008) and Udalski et al. (1999) places the first-overtone $M_I$ PL relation on the same scale as the fundamental mode one. To construct the Wesenheit PL relation for the different types of Cepheids, we took the $B$ and $I$ PL relations at a given period, and calculated $W_B$ using Equation (6).

The result, shown in the right panel of Fig. 9, has clearly reduced the scatter in the DDO210 Cepheid PL relation. While these two PL relations lie close in this Wesenheit plane, it appears that most of the Cepheids lie brighter than the AC PL relations and closer to the CC PL relations in this plane. Additionally, we observe the possible AC candidates (circles) as determined by the CMD analysis in Section 5.1 to lie on the same PL relation for the likely CCs (stars) extended to fainter magnitudes. This would seem to support this Cepheid population containing mostly, if not entirely, CCs. Finally, we draw attention to the two bright outliers on the short-period end of the $W_B$ PL relation. These stars are more likely second-overtone Cepheids since these pulsators have been observed to pulsate with shorter periods at a given magnitude when compared to the first-overtone pulsators.

5.3 Specific frequency of Anomalous Cepheids

The final test we perform to discern the nature of the Cepheids in DDO210 is to examine the specific frequency of the potential ACs. Mateo, Fischer, & Krzemiński (1995) first noted that the specific frequency of ACs (number per $10^5 L_{☉}$) is strongly correlated with both the absolute visual magnitude and mean metallicity of MW satellite dSphs. Pritzl et al. (2004, 2005) further extended the study of ACs to dSph orbiting M31 and discovered those galaxies to follow the same trends. Pritzl et al. (2005) also noted that Phoenix, a dTrans, follows the same trends as the dSph, indicating that these relations may hold independent of galaxy morphological type.

If we assume that this relation holds for all dwarf galax-
ies in the LG, then we expect the specific frequency of ACs in DDO210 to follow these same trends. We have therefore calculated the AC specific frequency in DDO210 assuming all of the 58 potential ACs identified in Section 5.1 are bona fide ACs. For this calculation, we have used an absolute magnitude of $M_V = -10.58$ mag (McConnachie et al. 2006), a surveyed area fraction for this dataset of 50% (Cole et al. 2014), and mean metal abundance of $[\text{Fe}/\text{H}] = -1.44$ dex (Kirby et al. 2013). We compare the AC specific frequency of DDO210 with the other dwarf galaxies in Fig. 10.

Clearly, DDO210 does not follow the same AC specific frequency trends as other LG dwarfs if we assume all potential ACs to be real. In fact, for DDO210 to fall in line with the trend for other dwarfs, our sample of Cepheids would need to contain $\leq 2$ ACs. Thus, we are left with two scenarios: 1) Most or all of these AC candidates are indeed true ACs, and the specific frequency trends do not hold for all dwarfs, or 2) The specific frequency trends do hold for DDO210, and only $\leq 2$ of these Cepheids are in fact ACs. Scenario 2) coupled with the AMR of Cole et al. (2014), the locations of the Cepheids in the CMD, and the Wesenheit PL relation for the Cepheids in DDO210 lead us to conclude that the majority of the Cepheids in this galaxy are CCs.

6 DISCUSSION

The main goal of this work was to investigate the properties of the pulsating variables in the context of the SFH of DDO210. The recent SFH analysis of Cole et al. (2014) provides an excellent comparison to this end. As we have already discussed, the metallicity of the RR Lyrae stars derived in this work agrees well with the AMR from Cole et al. (2014) at ages of $\sim11$ Gyr, but is inconsistent with their AMR for ages $\geq 12.5$ Gyr. Interestingly, their SFH shows a deep minimum in star formation rate at this 11 Gyr time bin. Those authors note that this drop is robust, and that the star formation rate at this time is only nonzero at the $\sim 2\sigma$ level. The presence of an RR Lyrae population with a mean metallicity of $[\text{Fe}/\text{H}] = -1.63 \pm 0.11$ confirms a weak, but nonzero star formation rate during this early epoch in DDO210.

We now turn to discussing our results on the context of massive galactic halo formation. The paradigm for the formation of the MW halo has held that a large part of it has formed through the accretion of dwarf galaxies closely resembling those found in the LG today. Extending this mechanism to other massive galaxies similar to the MW, it follows that the LG dwarfs should provide excellent windows to the systems that built many massive galaxies in general. However, as was pointed out in Section 4.2 the RR Lyrae populations in the dSph and UFDs of the LG appear fundamentally different than those found in the MW halo and GGCs. Fiorentino et al. (2015) attribute this difference to a difference in the metallicity of the ancient stellar populations from which the RR Lyraes formed. They show that the dSph and UFDs did not chemically enrich rapidly enough to produce the HASP RRab stars observed in the Galactic halo, GGCs, and more massive dwarfs like the LMC and Sgr. They find that galaxies need to have enriched to metallicities of $[\text{Fe}/\text{H}] = -1.5$ dex or more before $\sim10$ Gyr in order to produce these HASP RRab stars.

DDO210 appears to harbor an RR Lyrae population lacking in HASP RRab stars, similar to the dSph and UFDs. That these stars are metal-poor of the HASP threshold ($[\text{Fe}/\text{H}] = -1.63 \pm 0.11$ dex; see Section 1.1) is in agreement with the picture provided by Fiorentino et al. (2015). Those authors go on to estimate that no more than $\sim50\%$ of the Galactic halo mass could have accreted from these low-mass, metal-poor galaxies. Therefore, it is still possible
that some galaxies resembling DDO210 could be buried in the Galactic halo. However, it seems that the contribution of isolated, low-luminosity dTrans like DDO210 is at a similar level to that of the dSph and UFDs. Considering the low level of early star-formation implied by the RR Lyrae population and the isolation of DDO210, we conclude that galaxies resembling this one probably did not contribute a significant amount of mass to the Galactic halo.

Regarding the Cepheids, it is difficult to place strong constraints on the SFH from our sample given the unknown composition (ACs vs CCs?). We have shown that most of this sample is likely CC, implying that these stars formed within the past 500 Myr or so. To test this hypothesis further, we have applied the period-age relation from Bono et al. (2005) to our sample of Cepheids. Unfortunately, that study did not extend their exploration to metallicities as low as DDO210. Nevertheless, we continue with their most metal-poor period-age relation \( (Z = 0.004) \) in an effort to gain rough insight into the ages of these stars. The two period-age relations for the fundamental and first-overtone Cepheids take the form:

\[
\log t = 8.49 - 0.79 \log P \\
\log t = 8.41 - 1.07 \log P
\]

where \( t \) is the age of the Cepheid in years. We used the Wesenheit PL relation (See Section 5.2) in order to distinguish between fundamental and first-overtone Cepheids. Applying Equations (7) and (8) to these sets of Cepheids produced the age distribution shown in Fig. 11. This distribution indicates that, if these stars are all CCs, then these stars all likely formed within the past Gyr. Thus, we can compare these stars’ properties with the SFH of Cole et al. (2014) again. If we assume for the sake of comparison that the errors introduced by using a period-age relation for more metal-rich stars are relatively small \( (\lesssim 100 \text{ Myr}) \), then it seems that most of these stars were born around 300 Myr ago. Cole et al. (2014) examine the SFH of the past 1 Gyr in detail, and they find an enhancement in star formation rate at ages of 250-300 Myr. Thus under these assumptions, the properties of these CC candidates is fully consistent with their synthetic CMD analysis. We note that these ages are also in agreement with the analysis of McConnachie et al. (2006) where they compare theoretical isochrones to the position of the blue-loop stars on their \( V, (V - I) \) CMD. They find many of the blue-loop stars in DDO210 in the same region as our Cepheid sample to be \( \sim 300 \text{ Myr old} \).

The presence of stellar population gradients has been found to be a common characteristic of dwarf galaxies. In the case of DDO210, McConnachie et al. (2006) trace the distribution of different stellar populations and find that the radial profile of the young stars is different from the older RC and RGB stars. In particular, they find the youngest stars to confined to a small \( (\sim 0.3 \text{ kpc}) \) clump roughly one arcminute east of the centre of DDO210. We attempt to further examine this young star distribution through the radial distribution of the age of the Cepheids. In order to estimate where the clump of young stars lies in our data, we took the centroid of all of the Cepheids younger than 250 Myr as our fiducial centre. The projected distances (assuming a distance modulus calculated by the RR Lyrae stars) of the Cepheids from this point are plotted against their ages in Fig. 12, and it reveals that the youngest Cepheids are concentrated to within 0.4 kpc, consistent with the results of McConnachie et al. (2006). On the other hand, Cepheids older than 200 Myr extend almost twice that range in distance.

This point is further illustrated in Fig. 13, where we have plotted the 2 \( \sigma \) error ellipses for the mean positions.
Pulsating variables in DDO210

1. The age distribution of the Cepheid variables in DDO210.

2. The age of the Cepheid variables in DDO210 versus the radial distance from the centre of the young stars in the galaxy. It is striking to note that no stars younger than \( \sim 200 \) Myr are found beyond 0.3 kpc from the centre.

3. Interpretation of Fig. 13 is somewhat difficult with information available to us. This may indicate that the recent star formation has migrated away from the centre of the galaxy. Indeed, McConnachie et al. (2006) already suggested that such a scenario may have occurred within DDO210 through the process described by Dohm-Palmer et al. (2002) for Sextans A. To summarize the mechanism, star formation is induced on one edge of a gas cloud and thought to migrate through the cloud from instabilities triggered by the supernova and wind-driven shocks of the previous, adjacent star formation episodes. The Cepheids appear consistent with such a scenario occurring with DDO210, and in fact the centre of the youngest Cepheids in our sample lies \( \sim 15'' \) (\( \sim 70 \) pc) from the approximate centre of the young stars and corresponding H I 'dent' (black diamond in Fig. 13) discussed in McConnachie et al. (2006). On the other hand, the centre

Table 4. Mean positions and standard errors for each variable population.

| Variable type | RA (°)       | Dec (°)       |
|---------------|--------------|--------------|
| Young Cepheid | 311.7206±0.0052 | -12.8542±0.0031 |
| Old Cepheid   | 311.7148±0.0018  | -12.8466±0.0011  |
| RR Lyrae      | 311.7117±0.0026  | -12.8486±0.0011  |
of the older Cepheids in our sample lies much further from the centre of the young stars from McConnachie et al. (2006) at ∼180 pc.

As McConnachie et al. (2006) point out, there are other alternatives to explain the offset of the young stars from the galactic centre. For instance, it is possible that DDO210 interacted with some nearby system which could have potentially induced star formation away from the centre. However, the isolation of this galaxy renders this scenario rather unlikely. Another possibility that McConnachie et al. (2006) suggest is the recent capture of gas. However, if this mechanism was responsible for the formation of the youngest stars, then one would not necessarily expect the metallicity of these youngest stars to be similar to the older Cepheids unrelated to this captured gas. The fact that these Cepheids all appear to constitute one continuous population in the CMD and PL plane indicate that they must be of similar chemical composition, and therefore formed from related star formation events.

Finally, another scenario one might imagine to explain the spatial distribution of Cepheids in this galaxy is one in which all of these stars formed off-centre. In this case, the older Cepheids will have had more time to migrate from the original site of star formation. During this dispersal, the older stars have more time to be affected by the overall galactic potential, thereby orbiting the galactic centre as opposed to the natal star forming region. In the absence of any kinematic information for these stars, we cannot confirm this scenario. We do however note that recent theoretical work has shown that significant radial stellar migration in dwarf galaxies is not expected to occur over these short time-scales (Schroyen et al. 2013).

We should also note that such migrating star formation regions appear to occur within systems marked by solid-body rotation (Dohm-Palmer et al. 2002). As differential rotation acts to destroy substructure through shear, propagation of star formation across significant distances is less likely in such systems. On the other hand, galaxies with solid-body rotation allow for substructure to remain coherent for longer time periods, allowing this mechanism to more efficiently act. The galactic rotation curve for DDO210 from Begum & Chengalur (2004) shows that the central few hundred parsecs of DDO210 are likely undergoing solid-body rotation, further supporting the possibility of migratory star formation in this galaxy. Therefore, assuming these stars formed near where they are presently observed, we conclude the migratory star formation region the most likely explanation for the distribution of Cepheids in DDO210.

7 CONCLUSIONS

Using archival HST/ACS imaging of the LG dwarf DDO210, we have detected over 100 pulsating variable stars within this dwarf. These consist of 32 RR Lyrae stars and 75 Cepheids. The properties of these pulsating variables have been compared to the SFH analysis of Cole et al. (2014), showing that the SFH from Cole et al. (2014) is consistent with the properties of the RR Lyrae and Cepheid pulsators. In particular, we find the relatively small population of RR Lyrae stars to corroborate a weak but nonzero star formation rate at ages of ∼11 Gyr. We find one particularly metal-poor RR Lyrae that is also consistent with the large spread in the AMR produced by Cole et al. (2014) for these old ages. We find the behavior of the RR Lyrae stars in DDO210 to be consistent with those of other LG dwarfs in the period-amplitude plane. Specifically, this dwarf can be considered an Oo-intermediate system with a striking lack of HASP RRab stars.

As for the Cepheids, we argue that the majority of these stars are short-period CCs, however we cannot rule out the presence of some ACs with the information available to us. We have utilized a period-age relation for CCs in order to estimate the ages of these young pulsators. We find a peak in the Cepheid age distribution near 300 Myr, which agrees well with the SFH from Cole et al. (2014). The youngest of these Cepheids lie offset from the older Cepheids and the centre of the galaxy, confirming previous studies showing the young stars lie offset from the older stars in this galaxy. We conclude that this offset is likely resultant from a migration of star-formation, through a mechanism similar to what was proposed in Dohm-Palmer et al. (2002).

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