KECK SPECTROSCOPY OF GLOBULAR CLUSTERS IN THE VIRGO CLUSTER
DWARF ELLIPtical Galaxy VCC 1386

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ABSTRACT

We present the results of a Keck spectroscopic study of globular clusters associated with the Virgo Cluster dwarf elliptical galaxy (dE) VCC 1386. We analyze blue spectroscopic absorption lines from 3500 to 5500 Å for 13 globular cluster candidates and confirm that five are associated with VCC 1386. By comparing metal and Balmer line indices of these globular clusters with α-enhanced single stellar population models, we find that these systems are metal poor, with [Fe/H] > −1.35, and old, with ages >5 Gyr at 3 σ confidence, placing their formation at z > 1. This is one of the first spectroscopic studies of globular clusters surrounding dEs in a cluster, revealing that some low-mass galaxies in rich environments form at least part of their stellar mass early in the history of the universe. We further find that the luminosity-weighted stellar population of VCC 1386 itself is younger and more metal rich than its globular clusters, consistent with (V − I) colors from Hubble Space Telescope imaging. This implies that VCC 1386, like the Local Group dEs, has had multiple episodes of star formation. Globular clusters associated with low-luminosity systems, however, appear to be roughly as old as those associated with giant galaxies, contrary to the “downsizing” formation of their bulk stellar populations.

Subject headings: galaxies: dwarf — galaxies: individual (VCC 1386) — galaxies: star clusters — globular clusters: general

1. INTRODUCTION

Galaxy formation is thought by many to be a process whereby massive galaxies are built from smaller ones. This hierarchical process is now well modeled and is a natural outcome of a lambda-dominated universe with cold dark matter (e.g., Cole et al. 2000). Predictions based on simulations that incorporate these assumptions compare well with the large-scale features of the universe measured with microwave background experiments (e.g., Spergel et al. 2003) and large-scale galaxy surveys (Tegmark et al. 2004). However, there are several problems with the basic hierarchical model, mostly on the level of galaxies, and especially when predicting properties of the lowest mass systems (e.g., Moore et al. 1999). This includes predicting too many low-mass companions around galaxies like our Milky Way. These models also predict too few major mergers at z > 2 (Conselice 2006) and have a difficult time reproducing observations of all dE galaxies (Conselice et al. 2003b). Currently, it is assumed that differences between models and observations are due to an incomplete understanding of the physics behind star formation, although problems may also exist on a deeper more fundamental level as well.

Other tests of the hierarchical galaxy formation model are therefore needed to fully assess its assumptions and predictions. A potentially powerful way to do this is through examining low-mass galaxies, which are predicted to be, on average, the first galaxies in the universe. If the hierarchical model is correct, these low-mass galaxies are possibly survivors of the merger process and should contain some of the oldest stellar populations. Theory also predicts that the first galaxies should form in the densest environments (e.g., Springel et al. 2001; Tully et al. 2002), and thus cluster dwarf elliptical galaxies (dEs) potentially host the first stars that formed in the universe, perhaps before reionization (e.g., Bullock et al. 2000). This is particularly the case for dwarf galaxies that exist near the center of clusters, where the oldest stars in the nearby universe are predicted to be found (White & Springel 2000).

There is considerable evidence, however, that dEs, and lower mass galaxies in general, formed or entered clusters after the giant galaxies. For example, measurements of the integrated light in dEs reveal stellar population ages that are younger than the stars that make up giant elliptical galaxies (e.g., Poggianti et al. 2001; Caldwell et al. 2003; Rakos & Schombert 2004). Likewise, the faint end of the red sequence in clusters is not formed until z < 1 (De Lucia et al. 2004). This implies that the luminosity-weighted stellar populations of lower mass galaxies are younger than the stars in giant elliptical galaxies. This would appear to be an “antihierarchical” method of galaxy formation, such that the lowest mass systems formed after the more massive ones. This has been seen in field galaxies as well and has been described as “downsizing” (Cowie et al. 1996).

Curiously, it also appears that a significant fraction of faint dEs with M_g > −15 originate from a process different from that which formed the brighter dEs and elliptical galaxies. Evidence for this includes dE radial velocity distributions similar to those of infalling spiral galaxies (Conselice et al. 2001) and dEs with integrated light that appear young and/or metal rich (Conselice et al. 2003b; Rakos & Schombert 2004). These dEs are potentially produced from higher mass galaxies that became stripped of mass after infalling into clusters (e.g., Conselice 2002). However, the population of nucleated cluster dEs tend to have properties suggesting that they are the low-luminosity counterparts of giant elliptical galaxies, such as a high globular cluster specific frequency (Miller et al. 1998). Some dEs also fall along the color-magnitude relationship, while others do not (e.g., Rakos et al. 2001; Conselice et al. 2002, 2003b). It is thus not yet clear when, or how, low-mass galaxies form within a dense environment, or what their relationship is to dwarf galaxies in the Local Group and giant cluster elliptical galaxies.

We address these issues by studying the stellar population properties of globular clusters surrounding a dE, VCC 1386, in

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the Virgo Cluster. Globular clusters are ideal targets for this type of analysis, as they can be studied as single stellar populations and may retain clues to the earliest galaxy formation mechanisms (e.g., Forbes et al. 2004). Our target, VCC 1386, is a $M_V = -16.25 \ (L_\odot + 5)$ dE with a system of globular cluster candidates, 13 of which we obtain spectroscopy for using the Keck I Telescope. We confirm that five globular clusters are associated with VCC 1386, while three objects are foreground stars, with the remainder having too faint a signal to place constraints on membership. Our main conclusion is that some of the globular clusters surrounding VCC 1386 contain old and metal-poor stars, in contrast to the dwarf galaxy itself, which contains a younger and more metal-rich luminosity-weighted stellar population. This suggests that VCC 1386 contains multiple star formation episodes, and some globular clusters in this system are as old as, or older than, those in giant elliptical galaxies. Throughout this paper we use a distance to the Virgo Cluster of 16.7 Mpc (Whitmore et al. 1995).

2. OBSERVATIONS

We selected VCC 1386 globular cluster candidates from Wide Field Planetary Camera 2 (WFPC2) Hubble Space Telescope (HST) imaging in the F555W ($V$) and F814W ($I$) bands. This imaging is from an HST dE snapshot survey of the Virgo and Fornax Clusters (e.g., Lotz et al. 2004). Exposure times were 2 x 230 s in the F555W band and 300 s in the F814W band. For the VCC 1386 system, candidate globular clusters were selected on the basis of having $(V - I)_0$ colors consistent with previous observations of globular clusters, with $(V - I)_0 < 1.3$. We measured magnitudes in the $V$ and $I$ bands for each globular cluster candidate using a 2" aperture with APHOT on IRAF and corrected for Galactic extinction using the reddening corrections in Schlegel et al. (1998). On the basis of their colors, we obtained a sample of 28 globular cluster candidates.

The spectroscopic observations we present were taken with the Keck Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck I Telescope in 2004 February. Using one LRIS mask, we obtained spectroscopy for 13 globular cluster candidates. These clusters were located from near the center of VCC 1386 to a projected radius of 3 kpc. This system is shown in Figure 1, with the inner globular candidates with spectroscopy circled. This spectroscopy was acquired under good (seeing $\sim 0.6$) but unphotometric conditions, with a total exposure time lasting $\sim 7$ hr. We obtained spectroscopy with both the red and blue sides of LRIS (see Steidel et al. 2004 for a description of LRIS-B). On the blue side we used a 400 line mm$^{-1}$ grism blazed at 3400 Å, while on the red side we used the 600 line mm$^{-1}$ grating blazed at 5000 Å. This produced an effective resolution of 8 and 6 Å, respectively. The wavelength range probe was $\sim 3500$–5500 Å for LRIS-B, with wavelength calibration performed using HgKrXeNe comparison arc lamp spectra. The spectra was bias-subtracted, flat-fielded, and rectified using IRAF reduction techniques for multislit data, combining the various frames into a single one, and extracting the spectra for the individual globular clusters from this combination.

3. STELLAR POPULATIONS OF THE VCC 1386 GLOBULAR CLUSTERS

Using our spectra we identified features such as the calcium H and K lines and Fe lines, as well as Balmer lines such as H$\beta$ in our spectra. We derived from these lines the radial velocities of the globular clusters through cross-correlating the measured absorption lines with a known early-type galaxy spectrum and by identifying known lines by eye. Five of these systems (Nos. 1, 2, 3, 4, 6; Table 1) are at the radial velocity of the host galaxy, VCC 1386, at $\sim 1300 \text{ km s}^{-1}$ (Simien & Prugniel 2002). Three globular cluster candidates have radial velocities that place them within our own galaxy, and two of these are at a large projected distance from the center of VCC 1386. All of the confirmed globular clusters are within 1.5 kpc of the center of VCC 1386.

3.1. Metallicity and Age

We place constraints on the stellar populations that make up our globular cluster sample by using the spectra and colors of the five confirmed members. We use Lick line indices measured from the spectra to determine metallicities and ages of the globular clusters ( Worthey 1994; Worthey & Ottaviani 1997; Trager

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**Table 1**

| Number | R.A. (J2000.0) | Decl. (J2000.0) | $V$ | $V - I$ | H$\beta$ | H$\delta_F$ | H$\gamma_F$ | Mg b | (Fe) | [MgFe]$'$ |
|--------|----------------|----------------|-----|---------|---------|-----------|-----------|------|-----|--------|
| 1       | 12 31 50.7     | 12 38 48.7     | 22.8 ± 0.12 | 0.97 ± 0.32 | ...     | ...       | ...       | 0.74 ± 0.2 | 1.2 ± 0.3 |
| 2       | 12 31 50.8     | 12 39 05.5     | 22.6 ± 0.05 | 0.87 ± 0.16 | 2.5 ± 0.27 | 3.2 ± 0.4 | 2.0 ± 0.4 | 1.3 ± 0.2 |
| 3       | 12 31 52.1     | 12 39 13.3     | 22.3 ± 0.05 | 0.81 ± 0.15 | ...     | ...       | ...       | ...       | ...       |
| 4       | 12 31 51.1     | 12 39 23.3     | 21.9 ± 0.03 | 0.97 ± 0.11 | 2.9 ± 0.3 | 2.8 ± 0.4 | 3.7 ± 0.5 | ...       | 0.7 ± 0.5 |
| 6       | 12 31 50.3     | 12 39 38.1     | 22.6 ± 0.07 | 1.00 ± 0.17 | 2.4 ± 0.4 | 2.6 ± 0.3 | 2.6 ± 0.3 | ...       | 0.9 ± 0.4 |

**Note:** Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
et al. 2000; Thomas et al. 2003), although not every absorption feature could be measured for every globular cluster. We measured the equivalent widths of the Lick indices after smoothing our spectra by a wavelength-dependent Gaussian kernel to match the Lick ID resolution of ~9 Å (Worthey & Ottaviani 1997). Our data are not flux calibrated, but flux-calibrated indices are <1% different from non-flux-calibrated ones (e.g., Strader et al. 2003) and thus are not likely to contribute significantly to our error budget. We measured in our analysis the Balmer lines H$\beta$, H$\delta_F$, and H$\gamma_F$ and the metal lines Fe5270, Fe5335, and Mg$b$ using the updated passband and continuum wavelengths from Worthey (1994) and Worthey & Ottaviani (1997). Because we were unable to obtain Lick standard stars during our observations, we are not able to produce a direct offset between our indices and the Lick system. However, when using the same setup with LRIS under identical conditions, these offsets are found to be smaller than the observational errors and are thus not often applied (Brodie et al. 2005).

We determine the ages and metallicities of the stellar populations in our globular clusters through comparisons to the Bruzual & Charlot (2003) and Thomas et al. (2003) single stellar population (SSP) models. First, to constrain the ages of our globular clusters, we compare our measured Balmer indices (H$\beta$, H$\delta_F$, and H$\gamma_F$) with Bruzual & Charlot (2003) models (Fig. 2). The three horizontal lines in Figure 2 show the measured values of the H$\beta$, H$\delta_F$, and H$\gamma_F$ indices. The four lines overplotted show the modeled evolution of these indices with time. While several ages are possible for the globular clusters on the basis of these indices, they are generally consistent with being older than 5 Gyr, unless they have metallicities higher than [Fe/H] = −0.64, at a confidence >3 $\sigma$.

We cannot make definite conclusions regarding the ages of the globular clusters solely on the basis of Balmer indices. However, when we compare Bruzual & Charlot (2003) models of $V - I$ color and the H$\beta$ index, we find that old ages are preferred (Fig. 3). Figure 3 shows the modeled evolution of $V - I$ colors as a function of H$\beta$ at two different metallicities, [Fe/H] = −1.64 and −0.64. The evolution is such that the typical globular cluster H$\beta$ value of 2.5 Å is reached several times during the evolution of these SSPs. However, after about 1 Gyr, the colors of these SSP models are redder than $V - I \sim 0.6$. This effectively limits the possibility that these globular clusters are extremely young systems and is consistent with their being generally older than 5 Gyr.

Constraining metallicity is also not straightforward, as most metal lines such as Mg$b$ are influenced by the ages of stellar populations, as well as by their metallicity. However, by combining a metal index with a Balmer index, we can constrain the luminosity-weighted ages and metallicities of stellar populations. As such, we compare our measured indices to the $\alpha$-enhanced SSP models of Thomas et al. (2003), using the $\alpha = 0.3$ models for the three globular clusters (Nos. 2, 4, and 6) with a high enough signal-to-noise ratio to accurately measure these indices. We use the index $\langle$Fe$\rangle = 0.5(Fe5270 + Fe5335), the average of the Fe5270 and Fe5335 indices, as a measure of metallicity when compared with H$\beta$. We plot these values for our globular clusters in Figure 4a. The corresponding H$\beta$ versus $\langle$Fe$\rangle$ point for the body of VCC 1386 is also plotted in Figure 4, where H$\beta$ = 2.21 ± 0.24 and $\langle$Fe$\rangle$ = 2.15 ± 0.23 (Geha et al. 2003).

![Fig. 2.—Plots of a comparison between the Balmer indices for our globular clusters (H$\beta$, H$\delta_F$, and H$\gamma_F$, plotted as horizontal lines) and models from Bruzual & Charlot (2003) of how these indices evolve as a function of time. Four models are plotted at metallicities [Fe/H] = −2.2, −1.64, −0.64, and −0.33, from top to bottom, respectively. Error bars for these indices are plotted on the right-hand side of each panel at arbitrarily chosen ages of 20, 19, and 18 Gyr.](image)

![Fig. 3.—Plot of $V - I$ colors and the H$\beta$ index for VCC 1386’s globular clusters. Two Bruzual & Charlot (2003) evolutionary models at metallicities [Fe/H] = −1.64 and −0.64 are overplotted. Other metallicities, such as [Fe/H] = −2.2 and −0.33, show a similar evolution. The three points with error bars represent the values for our globular clusters. The average positions on this diagram where modeled ages reach 1, 5, and 9.5 Gyr are labeled.](image)
Figure 4 shows that VCC 1386’s globular clusters are located in the low-metallicity and old age part of the H\textsc{$\beta$}/Fe diagram, with ages ~8 Gyr and metallicities [Fe/H] < −1.35. By comparing with the Thomas et al. (2003) models, we can place statistical limits on the ages of our stellar populations. At 3\sigma confidence, all three globular clusters with measured H\textsc{$\beta$} and [Fe/H] indices are older than 5 Gyr and have a metallicity [Fe/H] < −0.33. When we compare the H\textsc{$\beta$} and the [(α/Fe)-insensitive index $[$MgFe$]$ $^0$ (see text)](http://www.annualreviews.org/doi/abs/10.1146/annurev.astro.46.060407.145201) (Thomas et al. 2003), we obtain the same constraints on ages and metallicities for globular cluster number 2 (Fig. 4b). We also use the M31 globular cluster relation between metallicity and (V − I)$_0$ color, [Fe/H] = (4.22 ± 0.39)(V − I)$_0$ − (5.39 ± 0.35) (Barmby et al. 2000), to place a photometric limit on the metallicities of these systems. Using this relationship, we find that the globular cluster metallicities vary between [Fe/H] = −1.3 and −1.9, consistent with their position on Figure 4.

Interestingly, one globular cluster (No. 4) has Balmer indices that are slightly larger than the other globular clusters. This globular cluster is potentially either more metal poor and as old as the others, or has a similar metallicity but is younger. This globular cluster is in fact located toward the center of VCC 1386 and therefore might have formed along with the bulk of the stellar populations that make up the body of VCC 1386. However, this globular cluster is not statistically inconsistent with having an old (>8 Gyr) age and a low metallicity, with [Fe/H] < −1.7.

Finally, in comparison to these globular clusters, the body of VCC 1386 itself has a higher (Fe) index at ~5\sigma confidence, but a similar H\textsc{$\beta$} index, giving it a higher SSP metallicity and a younger age (Fig. 4). A comparison of the distribution of (V − I)$_0$ colors for our globular clusters and the light profile of the dE itself (Fig. 5) reveals that VCC 1386’s globular clusters are more metal poor than the underlying light of VCC 1386, if we assume that (V − I)$_0$ color is a tracer of metallicity. The colors of the globular clusters are in all but one case bluer than the underlying light at a given projected distance from the center of VCC 1386. If we interpret these (V − I)$_0$ colors as a metallicity indicator, then these globular clusters have a lower metallicity than the dE itself at every projected distance.

### 3.2. Formation Timescales with [α/Fe] as a Constraint

Measuring the ratio of α elements to Fe, [α/Fe], allows us to place constraints on the star formation timescales of our globular clusters in VCC 1386. The small points and top axis give the radial distribution of colors for ~800 inner globular clusters surrounding M87 out to ~8 kpc (Kundu et al. 1999).
produce clusters. The reason is that Type II supernovae (SNe), which have younger light-weighted stellar population ages than giant evidence also exists that shows that dwarf galaxies in clusters systems in deep optical/NIR surveys (e.g., Cowie et al. 1996; In fact, it appears that lower mass galaxies finish forming after those in giants, this does not imply that all the stars in low-mass galaxies formed after most of the stars in the massive galaxies formed. A similar trend is seen for the Virgo dwarf galaxy VCC 1087, whose average metal indices are published in Strader et al. (2005). VCC 1087’s globular clusters have average and weighted standard deviation from the mean values of $H\beta = 2.35 \pm 0.06$, $(Fe) = 1.17 \pm 0.09$ and $Mg = 0.91 \pm 0.07$ (plotted in Fig. 4). Globular clusters in the Fornax dE orbiting the Milky Way also have similar indices (Strader et al. 2003), which are also plotted in Figure 4. This suggests that the globular clusters in dEs are very old (>5 Gyr) in both the Local Group and the Virgo Cluster, two vastly different environments. This interpretation may not, however, be unique for globular clusters around dEs, as Puza et al. (2000) find metal-rich globular clusters surrounding the dwarf galaxy NGC 3115 DW1.

Why do the integrated stellar populations in the main body of dEs appear to be younger than those in giant elliptical galaxies and younger than those in their own globular clusters? One possibility is that stellar population analyses are luminosity weighted and are therefore sensitive to any recent star formation (Trager et al. 2000). If an equal amount of star formation were to occur in a giant galaxy and a dwarf galaxy, it would be much easier to identify these new stars in the lower mass system. We know that dwarf galaxies in the Local Group, such as the Fornax dE, have multiple and extended star formation episodes (Buonanno et al. 1999), including old stars (Grebel & Gallagher 2004). It is currently impossible to rule out any recent star formation in giant elliptical galaxies that may be the counterpart of the younger generations of stars that form in dwarf galaxies after their globular clusters formed during later stages of star formation. With this interpretation may not, however, suggest that star formation does occur in elliptical galaxies at low redshift (Yi et al. 2005), yet the evidence for this in Virgo is currently ambiguous (Boselli et al. 2005).

If we assume that the star formation history of dwarf galaxies in Virgo is more extended than that of the giants, the obvious question is why it continues in low-mass galaxies but ends earlier in high-mass systems. There are several possible explanations for this. One is that feedback through supernova heating is more efficient in shallower potentials (and thus lower mass galaxies). When stars first formed in a dwarf halo, supernovae and stellar winds would have been very efficient at removing and heating gas. This feedback effectively slows down the star formation process compared to that of the giant galaxies. Later, if this gas still resided in the halo, it would cool and form stars. Alternatively, active galactic nucleus (AGN) feedback is more effective in massive galaxies where massive black holes exist. This AGN feedback would deposit enough energy to the point where it could halt star formation fairly quickly (e.g., Granato et al. 2004). It is not clear, however, whether low-mass dwarf galaxies contain black holes or go through an AGN phase, and thus it is possible that a corresponding processes in dwarf galaxies would not be as effective.

Delayed star formation in dEs induced by SN feedback, however, presents another problem, namely, why so few globular clusters formed during later stages of star formation. With
the possible exception of globular cluster number 4, it appears that all of the globular clusters in our sample are older and more metal poor than VCC 1386 itself. The colors of the globular clusters surrounding VCC 1386, even those for which we do not have measured indices, are furthermore bluer than the light from VCC 1386 at the same projected position. This is also seen for the dozens of other globular cluster systems studied in the Virgo and Fornax Clusters by the HST (Lotz et al. 2004). A possible explanation is that the Virgo Cluster formed the bulk of its mass between the time when the first globular clusters in VCC 1386 formed and later star formation that formed the remainder of VCC 1386. Due to tides, the now more massive galaxy cluster could have induced globular cluster evaporation in the lower dwarf potentials. The delay in star formation can also be accounted for by the reionization of the universe (e.g., Santos 2003), which appears to have occurred between $z \sim 6$ and 10. This would allow globular clusters to form before reionization, and any remaining gas inside these halos would photoevaporate. Later episodes of star formation would then occur once the gas inside these lower mass halos cooled, which likely occurred at $z < 1$. Cold gas is seen in roughly 15% of dEs in the Virgo Cluster (Conselice et al. 2003c), making this a possible scenario.

Finally, our results are consistent with some globular clusters surrounding giant elliptical galaxies originating from dwarf elliptical galaxies. Both color distributions and Lick indices for globular clusters surrounding giant galaxies in the Virgo Cluster overlap the values found for the globular clusters in VCC 1386 (e.g., Kundu et al. 1999; Cohen et al. 2003). For example, giant Virgo elliptical galaxies, such as M87, have blue color distributions that overlap the color distribution of our dE globular clusters (e.g., Kundu et al. 1999; Forbes et al. 2004; Fig. 5), suggesting that giant elliptical globular clusters may have formed partially from the accretion and mergers of lower mass systems. However, it is impossible for globular clusters in dwarf galaxies to form all the globular clusters around giant galaxies, as there is also a significant red globular cluster population surrounding giant elliptical galaxies (Zepf & Ashman 1993). A speculative explanation for this is that some of these red globular clusters form out of cold gas transported by an accreted dwarf galaxy, the same material from which the body of the dwarf galaxies we see today were formed.

More observations of globular clusters in dEs in rich environments, such as in Virgo and Fornax, are needed to determine the universality of these results and whether multiple populations of globular clusters with differing ages and metallicities exist within dwarf galaxies. However, due to the faintness of these globular clusters, a comprehensive study likely must await the advent of 20–30 m sized telescopes.

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REFERENCES

Barmby, P., Huchra, J. P., Brodie, J. P., Forbes, D. A., Schroder, L. L., & Grillmair, C. J. 2000, AJ, 119, 727

Poselli, A., et al. 2005, ApJ, 629, L29

Brodie, J. P., Strader, J., Denicoló, G., Beasley, M. A., Cenarro, A. J., Larsen, S. S., Kuntschner, H., & Forbes, D. A. 2005, AJ, 129, 2643

Bruzual, A. G., & Charlot, S. 2003, MNRAS, 344, 1000

Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525

Simien, F., & Prugnien, P. 2002, A&A, 384, 371

Spencer, D. N., et al. 2003, ApJS, 148, 175

Stetler, C. C., Shapley, A. E., Pettini, M., Adelberger, K. L., Erb, D. K., Reddy, N. A., & Hunt, M. P. 2004, ApJ, 604, 534

Strader, J., Brodie, J. P., Cenarro, A. J., Beasley, M. A., & Forbes, D. A. 2005, AJ, 130, 1315

Strader, J., Huchra, J. P., Forbes, D. A., Beasley, M. A., & Huchra, J. P. 2003, AJ, 125, 1291

Tegmark, M., et al. 2004, Phys. Rev. D, 69, 103501

Thomas, D., Maraston, C., & Bender, R. 2003, A&A, 399, 897

Trager, S. C., Faber, S. M., Worthey, G., & Gonzalez, J. J. 2000, AJ, 120, 165

Tully, R. B., Somerville, R. S., Trentham, N., & Verheijen, M. A. 2002, ApJ, 569, 573

White, S. D. M., & Springel, V. 2001, in The First Stars, ed. A. Weiss, T. G. (Berlin: Springer), 438

Kundu, A., Whitmore, B. C., Sparks, W. B., Lucas, R. A., Macchetto, F. D., & Bieretta, J. A. 1999, ApJ, 524, L19

Tiy, S. K., et al. 2005, ApJ, 619, L111

Zepf, S., & Ashman, K. 1993, MNRAS, 264, 611