Morphology-dependent trends of galaxy age with environment in Abell 901/902 seen with COMBO-17

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ABSTRACT

We investigate correlations between galaxy age and environment in the Abell 901/902 supercluster for separate morphologies. Using COMBO-17 data, we define a sample of 530 galaxies, complete at $M_V - 5 \log h < -18$ on an area of $3.5 \times 3.5$ (Mpc/h)². We explore several age indicators including an extinction-corrected residual from the colour-magnitude relation (CMR). As a result, we find a clear trend of age with density for galaxies of all morphologies that include a spheroidal component, in the sense that galaxies in denser environments are older. This trend is not seen among Scd/Irr galaxies since they all have young ages. However, the trend among the other types is stronger for fainter galaxies. While we also see an expected age-morphology relation, we find no evidence for a morphology-density relation at fixed age.

Key words: clusters: general; galaxies: evolution

1 INTRODUCTION

One of the long-standing mysteries of galaxy evolution is the origin of the morphology-density relation (Dressler 1980): high-density environments such as galaxy clusters are dominated by spheroidal galaxies while disk galaxies are the main population in the lower density field. This trend is also reflected in a colour-density relation (e.g. Balogh et al. 1999). High-density environments are dominated by old stellar populations, not only because the first galaxies started to collapse there, but also because star formation seems effectively suppressed still today (e.g. Kodama et al. 2001; Lewis et al. 2002; Gomez et al. 2003; Gray et al. 2004; Poggianti et al. 2006).

Kauffmann et al. (2004) found strong correlations between stellar age, morphology and the density of the local galaxy environment using the spectroscopic sample from SDSS DR2. They show quantitatively how stellar age increases with more spheroidal morphologies and towards denser environments. More recently, Ball et al. (2006) analyzed a sample of ~80,000 galaxies from SDSS DR4, and report that no residual morphology-density relation is seen at fixed colour. Conversely, a strong colour-density relation still remains at fixed morphology.

Colour alone provides only a crude estimate of stellar age as demonstrated by the colour-magnitude relation (CMR) of elliptical, passively evolving galaxies (Kodama et al. 1998): the slope of the CMR reflects a metallicity sequence with luminosity or stellar mass, while the offset of an individual galaxy from the CMR (its CMR residual) could reflect its stellar age. Of course, dust reddening affects the colour further, especially in the cluster Abell 901/902, which has a high fraction of dust-reddened galaxies on the red sequence (Wolf, Gray & Meisenheimer 2005).

In this paper we investigate these correlations in a single dense environment, that of the clusters Abell 901/902 observed by COMBO-17. The clusters are arranged in a very complex structure with filaments and four major concentrations. The hot gas content as seen in X-rays as well as the galaxy velocities suggest a highly dynamic environment that is far from virialized (Gray et al., in preparation). It may be a consequence of this action, that the cluster shows an unexpected, rich population of dusty star-forming galaxies accounting for more than a third of the red sequence.

In Sect. 2 we present the galaxy sample, and in Sect. 3 we discuss various SED-based stellar age indicators. Correlations between stellar age, galaxy morphology and local galaxy density are analysed in Sect. 4. In Sect. 5 we mention possible caveats of our study and finally discuss our results in Sect. 6. Throughout the paper, we use Vega magnitudes and the cosmological parameters $(\Omega_m, \Omega\Lambda) = (0.3, 0.7)$ and $H_0 = h \times 100$ km/(s Mpc).

2 DATA

This work is based on the data of the Abell 901/902 supercluster field in the COMBO-17 survey (see Wolf et al. 2004, for a general survey characterization). We start from the conservative cluster member sample defined by Wolf, Gray & Meisenheimer (2005), which contains 795 galaxies in a $30' \times 30'$ field. The sample was selected to have photometric redshifts in the range $z = [0.155, 0.185]$ and luminosities brighter than $M_V = -17$. At $M_V < -18.5$, this sample is $> 98\%$ complete, owing to a pho-
tometric distance of this cluster corresponds to a projected physical separation of a smaller volume along the line-of-sight. Hence, the effect of the photo-z errors, although the cluster occupies a truly much larger space densities, than a comparison with field objects of similar velocity intervals would suggest.

For these galaxies, we then determined visual morphological types on the deep R-band image of COMBO-17, that is co-added from 20,300 s of exposure with WFI at the ESO/MPI 2.2-m-telescope at La Silla, Chile. The image is characterized by a 0′′.8 PSF and a point-source detection limit of $R_{\text{mag}} \approx 26$. At the spectroscopic distance of this cluster $z = 0.165$, an angle of 1″ corresponds to a projected physical separation of 2.0/h kpc. We found that a reliable morphological classification was only possible for objects of $M_V < -18$, yielding a restricted sample of 530 galaxies. An average galaxy at $M_V = -18$ has a visible diameter of $\gtrsim 2′′$ ($\lesssim 3 \times$PSF), which may be the real reason for the limit.

The morphological classification was carried out by three independent authors (AAS, MEG, KL) and is described in more detail by Lane et al. (2006). For the purposes of this paper, four morphological classes are considered, which are E, S0, Sa/b, and Scd/Irr. While the spiral classes are broadly defined due to small detail by Lane et al. (2006). For the purposes of this paper, four morphological classes are considered, which are E, S0, Sa/b, and Scd/Irr. While the spiral classes are broadly defined due to small details, the spheroid classes try hard to discriminate E’s from S0’s although differences in their appearance are small and orientation-dependent.

This final sample is > 95% complete in terms of cluster members. A similarly defined field sample from COMBO-17 suggests, that statistically 37 out of the 530 galaxies are field contaminants. However, no correction for field contamination is attempted in this work, as it is particularly low among spheroids, which are at the focus of our attention.

3 COLOUR-MAGNITUDE RELATION AND STELLAR AGE INDICATORS

The COMBO-17 catalogue provides restframe $UBV$ magnitudes obtained by integrating the SED of the best-fitting template over the desired bandpasses. A restframe colour-magnitude diagram (CMD) is thus obtained for our sample, where the red sequence and blue cloud can be readily identified. Statistical errors in the restframe colour index $U - V$ are $\sim 0.03$ mag, and the zeropoint is uncertain by another $\sim 0.03$ mag resulting from uncertainties in the relative bandpass calibration. COMBO-17 colours represent a fixed-size aperture outside the atmosphere with identical spatial weighting in all bands. They are thus not representative of total object colours. The COMBO-17 classification estimates photometric redshifts, but also a measure of age of the stellar population and the amount of dust reddening (for details see Wolf, Gray & Meisenheimer 2005). In Fig. 1 we show the CMD with dust-poor (estimated $E_{B-V} < 0.1$) red-sequence galaxies emphasized as large points. A linear fit to the red sequence yields a colour-magnitude relation (CMR) of

$$ (U - V)_{\text{rest}} = 1.45 - 0.10(M_V - 5 \log h + 20) , $$

which fits in well with a redshift extrapolation of the evolving red sequence of field galaxies in COMBO-17 (Bell et al. 2004). Here, the slope is slightly steeper than usual (0.10 instead of 0.08), which may be a luminosity-dependent colour bias introduced by the fixed-size aperture photometry in COMBO-17. However, in the absence of internal colour gradients in galaxies this slope would be identical for both aperture and total galaxy colours.

We wish to study relations between stellar age and other galaxy properties, and use more advanced indicators than restframe colours, which are clearly affected by metallicity and dust reddening. We aim for an age ranking rather than absolute age determination. Also, the luminosity-weighted SEDs reflect more the time passed since the last major star formation event instead of a mass-weighted mean age. The formal COMBO-17 template fits to the observed SEDs will assist us in defining the colour/age measures. These templates are a time sequence after a burst of star formation assuming a fixed starting metallicity and an exponentially declining

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Trends of galaxy age in A901/902

Figure 3. Age-density relation at fixed morphology in A901/902. Number of objects and Student’s t statistic from a Spearman rank test are listed above the panels. The null hypothesis of no correlation between age and density is rejected at > 99.9%, > 99% and ∼ 95% for E, S0 and Sa/b galaxies, respectively, but accepted for Scd/Irr galaxies. Grey lines separate the density bins for the left panel of Fig. 5.

Figure 4. CMR residuals vs. density: Dust-free galaxies of all types are split into (overlapping, for better statistics) luminosity bins. No correlation is accepted at high luminosity but increasingly rejected towards lower $M_V$ at levels of < 50%, ∼ 80%, > 95% and > 99%. Number of objects and Student’s t statistic from a Spearman rank test are given. The errors of individual CMR residuals are 0.03 mag, while CMR slope errors mostly shift the zeropoints of each bin.

star-formation rate (SFR) with $\tau = 1$ Gyr. They include dust reddening from an SMC law ranging over $E_B-V = [0.0, 0.5]$. This age is a rough estimate on a possibly wrong scale, but age ranking would be recognized correctly, if galaxies of equal metallicity and star formation history (SFH) were considered. The present work is mostly concerned with spheroidal galaxies, where the bulk of the stellar population is old and large variations in SFH are not expected. We consider three different measures of galaxy colour or age of the stellar population:

A: The formal template age from the COMBO-17 fit. This age corresponds directly to the restframe colour which the galaxy would expose if its dust was removed. However, it ignores variations in metallicity and the details of the SFH of an individual galaxy. With the CMR being a metallicity sequence, this measure is not satisfactory for our purposes.

B: The CMR residual. This is a pure colour offset of galaxy $i$ from the CMR at its luminosity $(U-V)_i - (U-V)_{CMR}(M_V, i)$. Various works have suggested that the deviation of galaxy colour from the CMR at fixed luminosity, mass or velocity dispersion, is an age indicator (for a discussion, see Bernardi et al. 2005). This should work well for dust-free galaxies, where age drives colour when metallicity is fixed. However, the surprisingly large fraction of dusty red-sequence galaxies in A901/902 (∼ 35%) makes this approach only viable for part of our early-type sample.

C: A dust-corrected CMR residual or a CMR-corrected template age. This new measure is a combination of the two previous ones and alleviates the insensitivity of (A) to metallicity and the insensitivity of (B) to dust. It can either be expressed as the CMR residual a galaxy would have after taking away its dust. Or it can be expressed as the template age obtained by subtracting the colour offset $\delta(U-V)_{CMR} = -0.10(M_V - 5 \log h + 20)$ introduced by the CMR slope for each galaxy, keeping the known dust content fixed, and obtaining the age that corresponds to the corrected colour. The advantage of this approach is that it allows to take into account all three factors driving galaxy colour, age, metallicity and dust, albeit only at a crude level.

In the following, we will discuss relations between age, density and morphology based on age indicator (C). Indicator (B) produces very similar results as long as is not used with dusty galaxies, where it is a-priori not expected to work. This point is emphasized by Fig. 2 that plots CMR residual (B) against CMR-corrected age (C). The correlation between the two indicators is tight among dust-poor galaxies, but widens considerably for duster galaxies.

4 AGE-MORPHOLOGY-DENSITY RELATIONS

Age and density are continuous variables, while morphology is described in class bins, which can be ranked according to the prominence of the spheroidal component. In principle, morphology could be expressed as a continuous variable, if we used quantitative morphological descriptions.

We first investigate a plot of age vs. density at fixed morphologies (see Fig. 1), which in principle contains already the full information. For the galaxy types from E to Sb we find a correlation in the sense that galaxies in dense environments are on average older. They are confirmed by Spearman rank tests at > 99% significance for both E’s and S0’s, although the situation is less convincing to the eye for S0’s. For Sa/b galaxies we find that a null correlation is
rejected at >95% significance. Scd/Irr galaxies show no signs of any age-density relation.

Some authors have found age variations with mass along the red sequence (Caldwell et al. 2003, Clemens et al. 2006, and references therein), which would make our age ranking only hold at fixed galaxy mass. However, high-mass galaxies are then preferentially older and also found at higher-density, such that the true trend might be stronger than our result suggests.

While the Spearman rank correlation test makes no assumptions on the form of the data distributions, we still wish to point out that most galaxies in our sample are clustered around a density of 120 galaxies per (Mpc/h)^2 area. The densest regions with at Σ_{10} > 3000/(Mpc/h)^2 cover only a small area, as they correspond typically to a clustercentric radius of 1–2 h−1 Mpc. Also, our field is not large enough to reach out to densities Σ_{10} < 20/(Mpc/h)^2, compared to the COMBO-17 random field with Σ_{10} ≈ 4.7. However, these selection effects on density are entirely independent of galaxy age and morphology, because our sample is purely limited by luminosity and volume and complete with respect to other galaxy properties.

In Fig. 4 we split the population by luminosity instead of morphology. Also, we plot the measured CMR residual rather than the derived age, but then only for dust-poor galaxies. At high luminosity (brighter than M_ν, i.e., −20.5 for red galaxies in COMBO-17) we find no indication of a trend with environment. However, towards lower M_ν we find an increasing significance for a trend in the sense, that galaxies in high-density environments have more positive CMR residuals than those in lower densities. Thus, at high-density faint galaxies have redder CMR residuals than bright galaxies, while at low densities they have bluer residuals, keeping the mean CMR in the assumed place. An interesting corollary of this observation is a subtle environmental dependence in the slope of the CMR, to be explored in a forthcoming paper.

We now look at all possible 2-parameter correlations while keeping the third variable fixed. Fig. 5 shows them as mean quantities in one variable after binning the other two. First we look again at the age-density relation but this time in bins of morphological type and density. As before, we find a clear increase in age with density for E and S0 galaxies. There is a less significant trend for Sa/b spirals and no trend for Scd/Irr galaxies. The center panel of Fig. 5 shows a clear age-morphology relation at fixed density for all galaxy types and density. The age increases towards earlier type galaxies, from 1–2 Gyr for Scd/Irr’s to 5–8 Gyr for E and S0 galaxies. In fact, at all densities we find S0’s to be slightly younger than E’s. Finally, in the right panel we inspect a possible morphology-density relation at fixed age, but find no evidence for it. In all age bins, the mean density of the sample is practically independent of morphology.

5 CAVEATS

Our sample contains 530 galaxies, which are selected by photometric redshift and luminosity, and is more than 95% complete. The completeness is independent of stellar age, morphology or environment (surface density), three measures of galaxy properties with possible correlations among them. Observed correlations should thus not be the result of sample selection effects.

Measurements of all three galaxy properties are subject to statistical and possibly systematic errors. However, we believe that these can not lead to the presence or absence of the observed relations. The relations are clearly observed with both stellar age indicators (B) and (C). The indicators do not precisely measure mean stellar age but rather time passed since the last major star-formation event. Even then the absolute age scale is uncertain, while the age ranking should be reliable. A study by Bernardi et al. (2005) appears to rule out that CMR residuals are dominated by metallicity effects and confirms their interpretation as age effects. Trager et al. (2000) suggest that CMR residuals in age and metallicity are anticorrelated at fixed mass, implying a larger underlying age scatter than assumed from the colour residuals. In this case, we would observe a reduced signal from a truly stronger effect.

The morphology assessed by human classifiers from ground-based images is not reproducible. However, averaging the classifications from three persons allows to quantify and reduce noise. The weakest point is probably the discrimination between E and S0 galaxies. However, even mixing the bins for these two types would not remove any of the observed trends and relations.

On the whole, we believe that any possible systematic biases in morphology or age should be independent of each other and independent of environment. However, we have to guard ourselves against biases from luminosity-dependent galaxy properties such as metallicity, or in the presence of internal colour gradients also the fraction of light inside our fixed-size aperture defining the SED. When looking at the relation between density and the CMR residual in luminosity bins we eliminated these problems.

6 DISCUSSION

We have observed a clear trend of increasing age with increasing density of the environment for galaxies with spheroidal compo-
nents in the cluster A901/902. The significance of this age-density trend increases when going to fainter galaxies, while it is invisible at $M_V < -21$. In contrast, we found no evidence for any morphology-density relation at fixed galaxy age. 

**Kaufmann et al. (2004)** investigated relations between environment, morphology, SFH and mass of galaxies in the SDSS. Their sample represents a random galaxy field with their highest density bin corresponding to $\Sigma_{10} > 2/(\text{Mpc}/h)^2$ on our scale, which is a factor of ten below our lowest bin. From this they found very much the same relations as we do in the cluster: a declining star-formation rate and an increasing stellar age with increasing density are the strongest relation in place. A trend for older galaxies to be more spheroid-dominated is evident from their and our data, but has become textbook knowledge a while ago. Also, they find no evidence for an explicit morphology-density relation at fixed mass. 

**Haines et al. (2006)** also find a clear age-density relation in their analysis of the supercluster Abell 2199 from the SDSS DR4 data set. However, their result applies to the full galaxy population and is not differentiated by type. They observe, that fainter galaxies are generally younger and that the critical density for the marked increase in age is higher for fainter galaxies. It is difficult to compare our results directly to theirs, because we have no reliable absolute age measures and have deliberately eliminated the CMR slope from our age estimator. However, we still agree on the finding that faint galaxies have younger ages at lower density than at high density.

Also, **Smith et al. (2006)** have obtained strong evidence for an age trend with clustercentric radius among red-sequence cluster galaxies and suggest that the trend may be stronger for lower-mass galaxies. In our complex cluster environment, **Lane et al. (2006)** have compared trends of galaxy properties with environment using several measures of the latter: they suggest that the underlying relations are with local galaxy density, such as $\Sigma_{10}$ or dark-matter density, rather than clustercentric radius. Of course, in virialized clusters of regular shape one could not observe any difference between the two environmental measures. From our data set, we can confirm the age trend with local density. We have further identified that in Abell 901/2 this trend applies independently to E and S0 galaxies, and probably to spiral galaxies as well. Thus, the trend is not a simple result of the morphological mix changing with environment, but affects galaxies of all morphologies. We also confirm the strength of this trend to increase with decreasing luminosity. 

**Nelan et al. (2005)** have also reported an increased age scatter among lower-mass red-sequence galaxies in clusters. The right panel of our Fig. 1 shows the same result for our dust-poor red-sequence galaxies, an increased age scatter with lower luminosity. We note that this scatter is not a result of noise in our sample (that should be at the level of 0.03 mag). This is also consistent with the stronger age-density trend among fainter galaxies as seen in the right panel of our Fig. 4.

Statistically, the current density in the environment of a galaxy is correlated with the density at its birth. Thus, galaxies which are today in high density environments started their lives mostly in high density environments, regardless of their morphology. Hierarchical models of galaxy formation (e.g. **De Lucia et al. (2006)**) also indicate that galaxies in high-density regions started their lives (and forming stars) earlier and were exposed for a longer time to the environmental effects that could quench star formation, implying older average ages. Altogether, these results suggest that the primary relation among the parameters is the age-density relation. Age is also correlated with morphology, as old galaxies had more time to undergo interactions or mergers leading to bulge formation and/or the cessation of star formation. 

Massive red-sequence galaxies show no significant age trend in our relatively high-density environment, while evidence for field ellipticals being younger than cluster ellipticals (e.g. **Kuntschner et al. (2002)**) suggests an age trend appearing at densities below the regime of our study. In contrast, low-mass galaxies show an age trend across our higher-density regime, suggesting a mass dependence of the density regime in which galaxies lose their ability to form stars. This mass dependence is consistent with a picture in which massive galaxies terminate their star formation via feedback, while less massive galaxies have their SF suppressed by a dense environment. Future surveys of super-cluster environments would help to firm up these trends and determine their physical origin.

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