WITNESSING THE BUILD-UP OF THE COLOUR–DENSITY RELATION

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We investigate the redshift and luminosity evolution of the galaxy colour-density relation using the data from the First Epoch VIMOS-VLT Deep Survey (VVDS) on scales of $R = 5h^{-1}$Mpc up to redshift $z \sim 1.5$. While at lower redshift we confirm the existence of a steep colour-density relation, with the fraction of the reddest/bluest galaxies of the same luminosity increasing/decreasing as a function of density, this trend progressively disappears in the highest redshift bins investigated. Our results suggest the existence of an epoch (more remote for brighter galaxies) characterized by the absence of the colour-density relation on the $R = 5h^{-1}$Mpc scales investigated. The rest frame $u^* - g'$ colour-magnitude diagram shows a bimodal pattern in both low and high density environments up to redshift $z \sim 1.5$. We find that the bimodal distribution is not universal but strongly depends upon environment. Both the colour-density and colour-magnitude-density relations, on the $R = 5h^{-1}$Mpc scales, appear to be a transient, cumulative product of genetic and environmental factors that have been operating over at least a period of 9 Gyr. These findings support an evolutionary scenario in which star formation/gas depletion processes are accelerated in more luminous objects and in high density environments: star formation activity is progressively shifting with cosmic time towards lower luminosity galaxies (downsizing), and out of high density environments.

1 Introduction

There is a well known connection between galaxy properties and the environment wherein galaxies reside. These correlations extend smoothly over a wide range of density enhancements, from the extreme environment of rich clusters to very low densities, well beyond the region where the cluster environment is expected to have much influence.

A key question that still needs to be addressed is whether these environmental dependencies were established early on when galaxies first assembled (the so-called ‘nature’ hypothesis), or whether they are the present day cumulative end product of multiple processes operating over a Hubble time (density-driven evolution, the so-called ‘nurture’ scenario).

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A promising approach to addressing these issues involves extending observations beyond the local universe. Large and deep redshift surveys of the universe are the best available instrument to select a representative sample of the galaxy population over a broad and continuous range of densities and cosmic epochs. In this study, we use the VIMOS VLT Deep Survey, the largest (6582 objects), deepest (0.25 < \( z \) < 1.5), purely-magnitude selected (\( I_{AB} \leq 24 \)) redshift sample currently available, to explore the colour-density relation as a function of both luminosity and cosmic time. In particular the main goal of this investigation is to portray the colour-density relation at different epochs and evaluate eventual changes in its overall normalisation (Butcher & Oemler effect, Butcher & Oemler\(^1\)) and slope (Dressler effect, Dressler\(^2\)).

A more complete description of this work can be found in Cucciati et al.\(^3\)

2 The Data and the Environment Reconstruction Scheme

The VIMOS VLT Deep Survey (VVDS) in the VVDS-02h field has been conceived as a purely flux-limited (17.5 \( \leq I \leq 24 \)) survey (Le Fèvre et al.\(^4\)). The first-epoch VVDS-02h data sample extends over a sky area of 0.7×0.7 degrees\(^2\) (~37×37 h\(^{-1}\)Mpc at \( z = 1.5 \)), and has a median redshift \( z \sim 0.76 \). It contains 5882 galaxies with secure redshifts with 0.25 ≤ \( z \) ≤ 1.5. We adopt the cosmology \( \Omega_m = 0.3 \), \( \Omega_{\Lambda} = 0.7 \), \( h = H_0/100 \). All magnitudes are quoted in the AB system.

We characterized the environment surrounding a given galaxy, at comoving position \( \mathbf{r} \), by means of the dimensionless 3D density contrast \( \delta(\mathbf{r}, R) \) smoothed with a Gaussian filter over a typical dimension \( R \): \( \delta(\mathbf{r}, R) = [\rho(\mathbf{r}, R) - \overline{\rho}(\mathbf{r})]/\overline{\rho}(\mathbf{r}) \). Densities are estimated using appropriate weights to correct for various survey observational characteristics (sample selection function, target sampling rate, spectroscopic success rate and angular sampling rate). Underestimates of \( \delta \) due to the presence of edges have been corrected dividing measured densities by the fraction of the volume of the filter contained within the survey borders.

To compute densities we exploit all the galaxies in our flux-limited sample: there are advantages and drawbacks in this method, therefore as a complementary approach we have reconstructed the density field using also a volume-limited subsample of galaxies ((\( M_B - 5 \log h \) ≤ −20.0). As long as the two approaches suffer from different limitations, obtaining consistent results with both of them allows us to derive more robust conclusions.

We have paid particular attention to calibrate our density reconstruction scheme: we used simulated mock catalogues extracted from GalICS (Hatton et al.\(^5\)) to determine the redshift ranges and smoothing length scales \( R \) over which our environmental estimator is not affected by the specific VVDS observational constraints. We conclude that we reliably reproduced the underlying real galaxy environment on scales \( R \geq 5h^{-1}\)Mpc out to \( z = 1.5 \).

3 Results

In this section we present our results on the dependence of galaxy colours from local density, luminosity and redshift. For this analysis we use rest-frame (\( u^* - g' \)) colours, uncorrected for dust absorption, derived from rest-frame AB absolute magnitudes (see Ilbert et al.\(^6\)) as computed in the \( u^* \) and \( g' \) CFHTLS-MEGACAM photometric system.

3.1 The colour-density relation: redshift and luminosity dependence

We explored the combined dependence of the colour-density relation on redshift and luminosity. To this purpose, we selected different samples of galaxies, using as luminosity thresholds the values (\( M_B - 5 \log h \) ≤ −19.0, −19.5, −20.0, −20.5, −21.0) respectively. For each of these samples the fractions of the reddest ((\( u^* - g' \) ≥ 1.10) and bluest ((\( u^* - g' \) ≤ 0.55) galaxies are shown in Fig. 1 as a function of \( \delta \) in four different redshift bins. As specified in section 2 we computed
local densities also using a volume limited sample \( (M_B - 5 \log h) \leq -20.0 \). The results obtained with this recipe show the same trends as in Fig. 1 although a bit noisier (see Fig. 2).

Fig. 1 shows that not only the colour segregation weakens as a function of redshift for galaxies of similar luminosity, but, at a fixed redshift, it strongly depends on luminosity: for progressively brighter galaxies the colour–density relationship, as we know it in the local universe, appears at earlier cosmic times.

To quantify the statistical significance of our findings, we fitted the points plotted in Fig. 1 with a linear relation \( f = a + b \delta \), where \( f \) is the fraction of red or blue galaxies). Fig. 2 shows the slopes \( b \) and the associated 1 \( \sigma \) error bars as a function of redshift, for red (triangles) and blue (squares) galaxies, for the three subsamples limited at \( (M_B - 5 \log h) = -19.0, -20.0, -21.0 \) going from top to bottom. Left panel refers to Fig. 1 i.e. when density contrast is estimated using the full flux limited sample, while right panel refers to results obtained when density contrast is estimated using the volume limited sample. Arrows indicate the redshift bin where the colour–density relation, as we know it in the local universe, appears for the first time.

3.2 The colour-magnitude diagram: redshift and density dependence

We also explored the evolution of the distribution of galaxies in the colour-magnitude plane \((u^* - g') \) vs. \((M_B - 5 \log h)\) as a function of both redshift and environment.

In Fig. 3 the first 3 columns show the isodensity contours of the distribution of galaxies in different redshift ranges (from top to bottom as indicated on the right) and for different environments (from left to right as indicated on top). The difference between the over-dense and under-dense colour-magnitude distributions is shown in the 4th column. The 1st column shows that the bimodal distribution of galaxies in colour space, well established in the local universe (e.g. Strateva et al.), persists out to the highest redshift investigated \((z \sim 1.5)\). This analysis confirms and extends at higher redshifts previous results obtained with photometric redshifts out to \( z = 1 \) (e.g. Bell et al. Nuijten et al.). The 2nd and 3rd columns of Fig. 3 show that bimodality holds irrespective of environment out to \( z \sim 1.5 \).

We can discriminate finer environmental dependencies imprinted in the bimodal colour distribution by plotting the difference between the over- and under-dense colour-magnitude diagrams. The 4th column of Fig. 3 shows that the colour-magnitude distribution is not universal but strongly depends upon environment. At low redshift, and for any luminosity, there is a prominent excess of red objects in over-dense regions, while under-dense regions are mostly populated by blue galaxies. On the other hand, and most interestingly, moving towards higher redshifts the relative ratio of the two peaks of the bimodal distribution becomes mostly insensitive to environment (at \( 0.9 < z < 1.2 \)) with the hint of the development of a more pronounced peak of blue galaxies in high density regions in the last redshift bin \((1.2 < z < 1.5)\).

4 Discussion

Our study represents the first attempt to use a purely flux-limited redshift survey to explore the primordial \((z = 1.5)\) appearance of the colour-density and colour-magnitude diagrams from the densest peaks of the galaxy distribution down to very poor environments and faint magnitudes, on \( R = 5h^{-1}\text{Mpc} \) scales. Our findings can be summarised as follows:

a) The most striking result of this study is displayed in Fig. 1. The colour-density relation shows a dramatic change as a function of cosmic time. While at the lowest redshifts explored we confirm the existence of a strong colour-density relation, with the fraction of the red/(blue) galaxies increasing/(decreasing) as a function of density, at previous epochs blue and red galaxies seem to be mostly insensitive to the surrounding environment, and at the remotest epochs explored \((z \sim 1.5)\) even the most luminous red galaxies do not reside preferentially in high
density environments. At $z \sim 1$ there is evidence of absence of the color-density relation for medium luminosity galaxies. Moreover, there are hints that the well established local trend, which progressively disappears, eventually reverses in the highest redshift bins investigated ($\sim 1\sigma$ effect), suggesting that in remote look-back times the star formation activity was higher in higher density peaks, a property reminiscent of a similar characteristic of Ly-break galaxies (Foucaud et al. 10). The absence of the color-density relation at the highest redshift bins investigated implies that quenching of star formation was more efficient in high density regions.

b) The evolution of the colour-density relation depends on luminosity. Not only, at fixed luminosity, there is a progressive decrease of red objects as a function of redshift in high densities, but also, at fixed redshift, there is a progressive decrease of fainter red galaxies. This result implies that star formation ends at earlier cosmic time for more luminous/massive galaxies.

c) Not only the slope of the colour-density has changed, but also its overall normalisation: the relative fraction of the bluest objects was higher in the past in both high and low density regions and for both brighter and fainter galaxies. However, the observed drop in the star formation rate of blue objects in poor environments is weaker than in high density regions and is weaker for fainter galaxies. This indicates that the mechanisms driving galaxy formation and evolution operate with different timescales in different environments, and that star formation rate continues to be substantial at the present day in field galaxies, especially in the fainter ones.

We can interpret these findings by making some simplifying hypothesis. Let’s assume, to first order, that the adopted colour classes are a proxy for different star formation histories, bluer galaxies having experienced relatively recent star formation. In this case, the observed time dependence of the colour-density relation implies that star formation is differentially suppressed in high and low density regions. For galaxies of similar luminosity the drop in star formation rate occurred earlier in higher density environments, resulting in the red excess observed at present epoch, and progressively later in lower density regions, i.e. in the field, where a larger blue component is still observed. This suggests that some environment driven mechanism may be at work. The drop in star formation is also a function of luminosity (and therefore probably mass): truncation mechanisms are more efficient in brighter systems than in fainter ones.

From an observational side our analysis well agrees with the so called downsizing scenario, first suggested by Cowie et al. 11, but modified to take into account the observed environmental dependence. According to our observations, star formation activity is not only progressively shifted to smaller systems, but also from higher to lower density environments.

This result agrees remarkably well with our findings (obtained with the same sample) about the significant evolution of galaxy biasing out to $z \sim 1.5$ (Marinoni et al. 12). In that study we showed that, while at high redshift bright galaxies formed preferentially in the high matter-density peaks, as the Universe ages, galaxy formation begins to take place also in lower density environments. This result on biasing evolution provides a simple and intuitive way to introduce environment in the original downsizing picture: brighter galaxies start forming stars earlier and preferentially in higher density environments. This can explain, in a qualitative way, the observed evolution of the colour-density relation, i.e. the faster progressive building up of bright red galaxies in high density environments and the slower evolution for the fainter galaxy population.

d) The strengthening of the colour-density relation as a function of cosmic time implies that the colour distribution has been tightly coupled to the underlying density field at least over the past 9 Gyr: the main effect of this coupling is a marked dependence on environment of the colour-magnitude distribution. The early epoch flatness of the colour-density relation causes the bimodal colour distribution in high density regions to mirror the one in poor environments. However, as time goes by, the colour-density relation strengthens and the bimodal distribution gradually develops the present-day asymmetry between a red peak more prominent in high density environments and a blue one mostly contributed by field galaxies. This suggests that we have sampled the relevant time-scales over which physical nurture processes have conspired
to shape up the present-day density dependence of the colour-magnitude distribution.

We conclude that the colour-density and colour-magnitude-density relations are not the result of initial conditions imprinted early on during the primordial stages of structure formation and then frozen during subsequent evolution. Our results suggest a scenario whereby both time evolving genetic information (galaxy biased formation) and complex environmental interaction (star formation quenching) concurred to build up these relations.

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Figure 1: Fraction of the reddest ($(u^* - g') \geq 1.10$, triangles) and bluest ($(u^* - g') \leq 0.55$, squares) galaxies as a function of the density contrast $\delta$ in different redshift bins (columns) and for different luminosity limits (rows).
Figure 2: Best fit slopes (and their associated 1 σ error bars) of the fraction of reddest (triangles) and bluest (squares) galaxies as a function of δ for the four different redshift bins of Fig. 1 (left column) and for the same results obtained when δ is computed with a volume limited sample (right column). From top to bottom different limits in absolute magnitude are considered, as indicated on the right. The straight lines (and the shaded error bar area associated) are the result of the linear fit to the points shown. Arrows indicate the redshift bin where the colour–density relationship, as we know it in the local universe, appears for the first time.

Figure 3: The first 3 columns show the isodensity contours of the distribution of galaxies in the \((u^*-g')\) vs. \((M_B-5\log h)\) plane: rows are different redshift ranges (labels on the right) and columns are different environments (labels on top). The grey scale is normalised to the total number of objects contained in each panel. The difference between the over-dense and under-dense colour-magnitude distributions is shown in the 4th column. 1 − 2 − 3 − σ levels of significance in the difference are shown using red continuous lines (positive differences), and blue dotted lines (negative differences). The thicker lines correspond to 1σ level.