The Butcher–Oemler effect at $z \sim 0.35$: a change in perspective

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ABSTRACT

In this paper we focus on the much debated Butcher–Oemler effect: the increase with redshift of the fraction of blue galaxies in clusters. Considering a representative cluster sample made of seven groups/clusters at $z \sim 0.35$, we have measured the blue fraction from the cluster core to the cluster outskirts and the field mainly using wide-field Cerro Tololo Inter-American Observatory images. This sample represents a random selection of a volume complete X-ray selected cluster sample, selected so that there is no physical connection with the studied quantity (blue fraction), to minimize observational biases. In order to statistically assess the significance of the Butcher–Oemler effect, we introduce the tools of Bayesian inference. Furthermore, we have modified the blue fraction definition in order to take into account the reduced age of the Universe at higher redshifts, because we should no longer attempt to reject an unphysical universe in which the age of the Universe does depend on redshift, whereas the age of its content does not. We have measured the blue fraction from the cluster centre to the field and we find that the cluster affects the properties of the galaxies up to two virial radii at $z \sim 0.35$. Data suggest that during the last 3 Gyr no evolution of the blue fraction, from the cluster core to the field value, is seen beyond that needed to account for the varying age with the redshift of the Universe and of its content. The agreement of the radial profiles of the blue fraction at $z = 0$ and $z \sim 0.35$ implies that the pattern infall did not change over the last 3 Gyr, or, at least, its variation has no observational effect on the studied quantity.

Key words: galaxies: clusters: general – galaxies: evolution.

1 INTRODUCTION

The nature and the time-scale of the processes that shape galaxy properties in clusters and groups are still unclear. The presence of a hot intercluster gas observed in X-rays should have a role in shaping some galaxy properties (e.g. Gunn & Gott 1972). The window opened by the redshift dependence of the galaxy properties has been used to set constraints on the time-scales of the processes (e.g. Butcher & Oemler 1978, 1984; Dressler et al. 1997; Stanford, Eisenhardt & Dickinson 1998; Treu et al. 2003). However, the observational evidence of the environmental effect is still uncertain. For example, the existence of a Butcher–Oemler (BO) effect (Butcher & Oemler 1984), i.e. the fact that clusters at higher redshift have a larger fraction of blue galaxies, f_b, is still controversial. The controversy is raised by two criticisms concerning measurements and sample.

Andreon et al. (2004, hereafter ALI04) analyse three clusters at $z \sim 0.7$ without finding evidence of a high blue fraction with respect to $z \sim 0$. They also show the drawbacks of the various definitions of f_b adopted in the literature. They conclude then that '20 yr after the original intuition by Butcher & Oemler, we are still in the process of ascertaining the reality of the effect'. The same work put in a different perspective the results of Rakos & Schombert (1995), clarifying the fact that even if all the galaxies in the Universe are passively evolving, the blue fraction will be $f_b \approx 1$ at $z \gtrsim 0.7$ in the Rakos & Schombert (1995) scale. Therefore, the very high fraction they found at high redshift does not require any special mechanism to account for the present-day counterparts other than ageing. ALI04 introduce also a first discussion about the difficult task of measuring the error on f_b, given the observations, showing that at least some previous works have underestimated errors and, by consequence, overstated the evidence for the BO effect. The role of the inference, the logical step going from the observed data to the true value and its error, has been further elaborated in D'Agostini (2004) in the more general case of unknown individual membership for the galaxies.

Kron (1994) claimed that all the 'high' redshift clusters known in the early 1980s ($z \approx 0.3$–0.5) were somewhat extreme in their properties, and this was precisely the reason why they were detected. Andreon & Ettori (1999) quantify this issue, and show that many of the clusters compared at different redshifts have also different

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masses (or X-ray luminosities), in such a way that 'we are comparing unripe apples with ripe oranges in understanding how fruit ripens' (Andreon & Ettori 1999). Together with Allington-Smith et al. (1993) and Andreon & Ettori (1999), ALI04 show that the optical selection of clusters is prone to produce a biased – hence inadequate – sample for studies on evolution because at larger redshifts it naturally favours the inclusion in the sample of clusters with a significant blue fraction. They show that clusters with a blue fraction as the observed ones are over-represented in optical cluster catalogues by a factor of 2, with respect to identical clusters but without a bursting population.

There is therefore a compelling need to study the properties of galaxies in clusters at intermediate redshift ($z \approx 0.35$), avoiding the bias of an optical selection, by choosing clusters of the same mass as present-day studied clusters to avoid an 'apples versus oranges' issue. This is the aim of this paper, where we present a BO-style study of a small but representative sample of seven clusters, X-ray selected, of low to average mass (velocity dispersion) and at intermediate redshift.

The layout of the paper is the following. In Section 2 we present optical imaging and spectral data. In Section 3 we show that the studied sample is both representative and X-ray selected. We revisit in Section 4 the definition of the blue fraction, in order to account for the reduced age of the Universe at higher redshift. In Section 5 we present some technical details. The results are summarized in Section 6, whereas in Section 7 we discuss the relevant results published in the literature and some final conclusions. In the appendices we present a Bayesian estimate of cluster velocity dispersion, richness and blue fraction.

We adopt $\Omega_\Lambda = 0.7$, $\Omega_{\rm m} = 0.3$ and $H_0 = 70$ km s^{-1} Mpc^{-1}.

2 THE DATA AND DATA REDUCTION

2.1 Photometry

We use the same imaging data as Andreon et al. (2004a), with some additional observations taken in 2002 with the same instrument and telescope. Briefly, optical *R*- and *z'*-band ($\lambda_c \sim 9000$ Å) images were obtained at the Cerro Tololo Inter-American Observatory (CTIO) 4-m Blanco telescope during three observing runs, in 2000 August, 2001 November and 2002 September with the Mosaic II camera. Mosaic II is a 8k × 8k camera with a 36 × 36 arcmin^2 field of view. Typical exposure times were 1200 s in *R* and 2 × 750 s in *z'*. Seeing in the final images was between 1.0 and 1.4 arcsec FWHM in the 2002 September and 2001 November runs, and between 0.9 and 1.0 arcsec FWHM during the 2000 August run. The useful nights of the three observing runs were photometric. Data have been reduced in the standard way (see Andreon et al. 2004a, for details).

Source detection and characterization were performed employing SEXTRACTOR v2 (Bertin & Arnouts 1996). Colours and magnitudes are computed within a fixed 5-arcsec radius aperture. A larger aperture, for colours, is used here with respect to Andreon et al. (2004a), where 1.9 arcsec was used, in order not to miss any potential star formation occurring at radii not sampled by the previously adopted aperture. Of course, the results of that paper are unaffected by our present aperture choice.

Object magnitudes are quoted in the photometric system of the associated standard stars: *R* magnitudes are calibrated with Landolt (1992) stars, while *z'* magnitudes are calibrated with Sloan Digital Sky Survey (SDSS; Smith et al. 2002) standard stars. We keep *R* and *z'* magnitudes in their system (i.e. Vega and SDSS, respectively).

Table 1. The cluster sample.

Name	z	N_z	σ_v (km s^{-1})	Error (km s^{-1})	r_{200} (Mpc)
XLSSC 024	0.29	11	430	96	1.0
XLSSC 028	0.30	8	376	98	0.8
XLSSC 009	0.33	12	236	52	0.5
XLSSC 010	0.33	11	367	96	0.8
XLSSC 016	0.33	5	915	294	2.0
XLSSC 006	0.43	39	837	106	1.7
XLSSC 012	0.43	12	741	165	1.5

2.2 Spectroscopy

Our clusters have been observed spectroscopically at Magellan, the New Technology Telescope or the Very Large Telescope (see Willis et al. 2005). Redshifts for a minimum of five up to 39 cluster members have been acquired per cluster with typical individual errors on redshifts of 50–150 km s^{-1} (depending on instrument, exposure time, etc.), as detailed in the mentioned papers.

Velocity dispersions are computed using the Beers, Flynn & Gebhardt (1990) scale estimator, as detailed in the appendices and are listed together with their errors in Table 1.

3 THE CLUSTER 'APPLES VERSUS ORANGES' ISSUE

As discussed in the introduction, the cluster selection criteria should not bias the targeted measurement (the blue fraction). As mentioned, the optical selection, especially if performed in the blue-band rest frame, boosts by construction the blue fraction at high redshift, unless some precautions are taken. The X-ray selection is useful because the cluster X-ray emissivity is not physically related, in a cause–effect relationship, to the colour of cluster galaxies, the other factors (e.g. mass, dynamical status, etc.) being kept fixed. Fairley et al. (2002) and Wake et al. (2005) exploit a similar X-ray selection, for a cluster sample much more (the former) or slightly more (the latter) massive (X-ray bright), but statistically uncontrolled.

The cluster sample studied in this paper is not an uncontrolled collection of clusters, but a random sampling of an X-ray flux limited sample of clusters in a narrow redshift range ($0.29 \lesssim z < 0.44$), drawn from the ongoing *XMM* Large-Scale Structure (*XMM*-LSS) survey (Pierre et al. 2004; Pierre et al., in preparation). The clusters actually used in the present paper are listed in Andreon et al. (2004a), or presented in a future catalogue. The sample studied here is a purely X-ray selected one drawn from a sample constructed using both an X-ray and optical selection criteria (the *XMM*-LSS survey), as clarified below. We refer to Pierre et al. (2004) for details about the *XMM*-LSS survey, and we discuss here only some relevant points.

One great advantage of a volume complete sample (or a random sampling of a volume complete sample) over an uncontrolled one is that each object has a chance of occurring that is proportional to its number density, i.e. it occurs in the sample with the same natural frequency as it occurs in the Universe. The above property is especially useful when computing ensemble averages (such as composite clusters), because it makes the statistical analysis straightforward. Instead, averages performed over uncontrolled samples (e.g. combined 'clusters' formed by staking clusters from uncontrolled lists) lack predictive power because it is unknown how representative the sample is. An astronomical example, together with a real-life application of the above concept, is discussed in Section 6.3.1

3.1 Malmquist-like (or Eddington-like) biases on f_b: redshift range selection

The precise choice of a redshift range largely depends on the quality of the available optical photometry and on the availability of velocity dispersions. The lower redshift limit ($z \sim 0.29$) has been chosen because of saturation issues: our images are exposed too long for brighter objects and their cores saturate, because exposure time has been originally optimized for the detection of $z \sim 1$ galaxies. The fuzziness of the nearest redshift limit is a result of varying seeing conditions and sky brightness during the observing runs.

The upper redshift limit ($z = 0.44$) comes from our desire to obtain a complete and unbiased sample. At $z > 0.44$ not all clusters have a known velocity dispersion, and it is legitimate to suspect that clusters without a known σ_v have a different blue fraction from clusters with a known σ_v, all the remaining parameters being kept fixed. Indeed, a cluster with a larger number of red galaxies has, observationally, a better chance of having a larger number of confirmed members than an equally rich, but poor in red galaxies, cluster, because background galaxies are more abundant among blue galaxies in percentage. Clusters rich in blue galaxies may have so few confirmed members that a cluster velocity dispersion cannot be computed with sufficient accuracy. Therefore, a cluster with a small blue fraction has a better chance to have a measured velocity dispersion than one with a large blue fraction. Below $z = 0.44$, all clusters have a known velocity dispersion and this problem does not arise.

In general, an upper redshift limit is needed for another reason: we want the faintest considered galaxies to be still affected by a negligible photometric error (see below), because it is quite dangerous to attempt to correct the blue fraction for the bias induced by photometric errors. In fact, the uneven colour distribution of galaxies (for example $f_b = 0.2$ means that more than 80 per cent of the galaxies have colours in a narrow red colour range, and the remaining 20 per cent are spread over a large blue colour range) and errors on colours of 0.2-mag amplitude produce a large Malmquist-like (or Eddington-like) bias, difficult to correct for without knowing the galaxy colour distribution, as first explained by Jeffreys (1938). The Eddington (1940) reply to the Jeffreys (1938) paper clarifies that improved values, i.e. corrected by the error measurements, 'should not be used for any kind of statistical inquiry' in good agreement with Jeffreys (1938). If the ultimate limit of the measurements lies in photometric errors, it is perhaps preferable to increase the quality of the photometry, rather than increasing the size of the sample, and therefore we prefer to have a small, but high-quality sample, than a large, low-quality sample.

Malmquist-like biases affect our blue fraction determination at $z > 0.44$, and therefore are of no concern for our analysis. However, they may be a concern for other similar works. The above Malmquist-like bias, joined to the use of data with a fixed quality (such as those coming from surveys), both unduly increase the observed fraction of blue galaxies with redshift, simply because galaxies become fainter and photometric errors increase with redshift. The above effect has nothing to do with the BO effect, of course, because the amplitude of the effect depends on the data quality, not on the galaxy properties.

3.2 Which selection criteria?

The sample from which we have drawn our clusters is formed by all clusters detected both in X-rays and in the colour space. Details about the colour detection can be found in Andreon et al. (2004a,b).

At the redshift studied in this paper, clusters stand out in the colour-space, and also in the direct-space (i.e. in the sky plane) as shown in section 3.2 of Andreon et al. (2004a), i.e. the probability to miss in the optical a cluster in the considered redshift range is virtually zero. In particular, clusters at $z \leqslant 0.29$ stand out in the direct-space (i.e. in images) so conspicuously that their brightest galaxies saturate the instrument (exposure time is tuned for $z \sim 1$ galaxies). Can a cluster be unnoticed when its galaxies (almost) saturate the instrument? Therefore, even if in principle our cluster sample is drawn from a sample that uses two criteria (X-ray emission and colour detection), at the studied redshifts the colour selection does not bias the cluster selection because it does not filter out any object. To check the above, during the spectroscopic campaign we devoted a (small) fraction of time to spectroscopically confirm candidates not meeting the colour detection. None turns out to be confirmed in the considered redshift range, showing that if clusters of galaxies not detectable in the colour-space do exist, they are so rare that they are not likely to occur in a sample like ours. As an independent check, we spectroscopically confirmed colour-detected clusters without detectable X-ray emission, at the same and higher redshift, showing that the optical selection goes deeper in the cluster mass function than the X-ray selection. One such an example, RzCS 001 at $z = 0.49$, is listed in Andreon et al. (2004a). Another example, RzCS 052 at $z = 1.02$, is studied in Andreon, Punzi & Grado (2005). The presence of other clusters deliberately not studied in this paper in the very same studied volume of the Universe, such as RzCS 001, emphasizes once more that we are studying an X-ray selected cluster sample and clarifies that the adopted selection is a deliberated choice in order to avoid the bias of the optical selection at high redshift, not an obliged choice dictated by our ignorance about which other clusters are present in the studied volume of the Universe.

3.3 Random sampling from a complete sample

Inside the selected redshift range, we removed all clusters with r_{200} radii overlapping each other in the sky plane, or which exceed the studied field of view of each individual CTIO pointing (~ 0.3 deg^2 area, to keep uniform quality all across the area), as well as one XLSSC cluster that lacks an obvious centre. These (observational-driven) cluster selections are independent of the cluster blue fraction and hence produce no biases. Therefore, our sample constitutes a random sampling of *XMM*-LSS clusters in the selected redshift range.

3.4 Details about the X-ray selection

As mentioned, our sample is drawn from the *XMM*-LSS survey, and therefore our sample inherits its advantages and limitations. To a first approximation, the survey is flux-limited, and therefore brighter clusters, visible over larger volumes, are in principle over-represented in the survey. However, here the studied redshift interval is small ($\Delta z = 0.14$), and the effect should be minor.

Furthermore, the *XMM*-LSS survey is surface brightness limited too, like most existing surveys, in spite of the use of wavelets in the detection step to mitigate surface brightness effects. Extensive numerical simulations (Pacaud et al., in preparation) show that, for core radii typical of the studied objects, detectability is larger than 90 per cent for all our objects.

X-ray fluxes inside half the optical r_{200} radius (computed as specified in Section 5) were computed in the 0.5–2 keV band from MOS1, MOS2 and pn merged images processed as in Chiappetti et al. (2005). We assumed a Raymond–Smith spectrum with

$kT = 2$ keV and $z = 0.35$, and the average galactic column density in the *XMM*-LSS (Dickey & Lockman 1990). We found values for our system in the range $0.3 \lesssim Lx \lesssim 16\,10^{43}$ erg s^{-1} cm^{-2} in the 0.5–2 keV band.

To summarize, the studied sample has $0.3 \lesssim Lx \lesssim 16\,10^{43}$, and it has been selected in a redshift–luminosity–surface brightness region where detectability is near 100 per cent, so that each cluster has the same probability of occurring in our sample as in the Universe.

4 THE GALAXY 'APPLES VERSUS ORANGES' ISSUE

Butcher & Oemler (1984) define the fraction of blue galaxies in the cluster, f_b, as being the fraction of galaxies bluer, by at least $\Delta = 0.2$ mag in the *B–V* rest-frame, than early-type galaxies at the cluster redshift (the cluster red sequence). The galaxies have to be counted down to a given absolute magnitude, which is chosen to be $M_V = -19.3$ mag in our cosmology (-20 mag in BO cosmology), within a reference radius that encompasses a given fraction of the cluster. Moreover, galaxies located in the background or foreground of the cluster must be removed, for example by statistical subtraction.

The actual limiting magnitude used in the BO paper is, at the BO high-redshift end, brighter than $M_V = -19.3$ mag in our cosmology (-20 mag in the BO cosmology) as shown by de Propris et al. (2003), i.e. different from what the BO definition requires. A brighter limiting magnitude at higher redshift is the correct choice if one wants to track the same population of galaxies at different redshifts, because of average luminosity evolution experienced by galaxies. Galaxies having $M_V = -19.3$ mag at $z = 1$ are now (at $z = 0$) much fainter than the $M_V = -19.3$ mag cut. A fixed magnitude cut therefore does not select similar galaxies at different redshifts, whereas an evolving limit does. Therefore, we have adopted an evolving mag limit, as actually adopted by BO themselves. An evolving limiting magnitude has also been adopted by de Propris et al. (2003), Ellingson et al. (2001) and ALI04 in their BO-style studies.

ALI04 discuss the large impact that apparently minor differences on the f_b definition have on the observed f_b. They found the following.

(i) The reference colour of the early-type galaxies to be used is the observed colour of the red sequence, and not the colour of a present-day elliptical, unless we are happy with an evolving f_b fraction for a sample of galaxies passively evolving.

(ii) The reference radius should scale with the cluster size, and not be a fixed metric radius, potentially sampling the centre of rich and large clusters and the whole cluster for small groups (another 'apples versus oranges' issue).

(iii) A unique Δ should be taken (equal to 0.2 in the *B–V* rest frame). If different values are chosen at different redshifts, it becomes difficult to compare populations selected with heterogeneous choices.

Let us discuss, and revise, the Δ choice.

There is little doubt that galaxies at higher redshift have younger stars than present-day galaxies, as measured by the fact that the reddest galaxies have a colour that becomes bluer in the rest frame with increasing redshift (e.g. Kodama et al. 1998; Stanford et al. 1998; Andreon et al. 2004a). This is also the natural outcome of the current cosmological model that allocates a shorter age of the Universe at higher redshifts. At the time of the BO paper, the measurement of the blue fraction was a valuable evidence to rule out a non-evolving universe. However, if the aim of deriving the f_b fraction is to measure an evolution beyond that due to the younger age of the Universe at high redshift, we propose a different choice for Δ, using an evolving spectral template in order to coherently separate blue galaxies from red galaxies. This is also an observationally obliged choice, as shown below.

Fig. 1 clearly illustrates our choice. The left panel shows the rest-frame *B–V* colour of $\tau = 1$ (upper curve) and $\tau = 3.7$ (lower curve) Bruzual & Charlot (2003) stellar populations of solar metallicity for exponentially declining star formation rate models, where

Figure 1. Left panel: rest-frame *B–V* colour of a $\tau = 1$ Gyr and $z_f = 11$ stellar population [top line (red online), mimicking an E], and a stellar population having the same z_f but being 0.2 mag bluer today (i.e. $\tau = 3.7$ Gyr, $z_f = 11$), referred to in this paper as Sa [bottom line (blue online)]. Right panel: R–z' colour difference in the observer rest frame between the two above stellar populations (solid line). The dotted line represents the difference for the case of non-ageing stellar populations. Dotted circles are derived using the Coleman et al. (1980) (non-evolving) templates. The two vertical (green online) delimiters mark the redshift range probed in this paper.
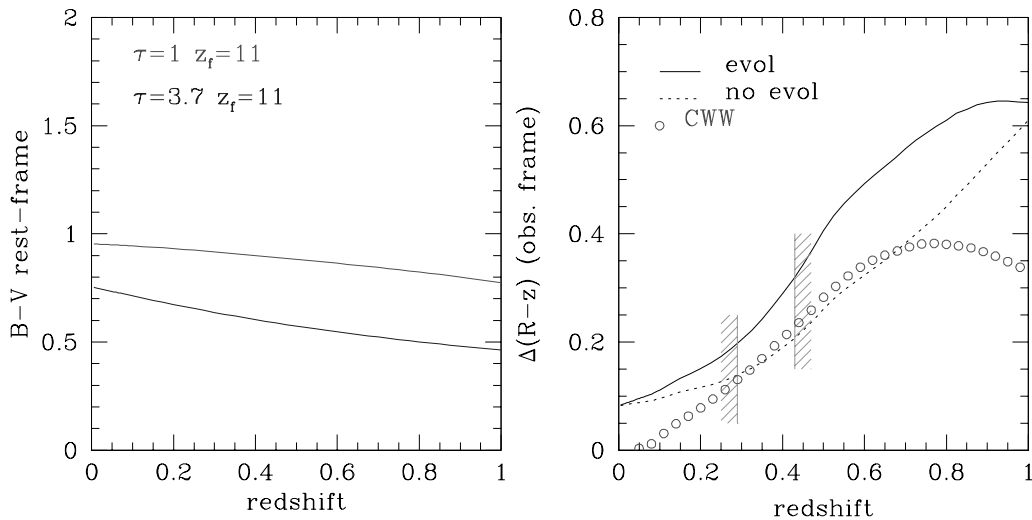
τ is the e-folding time in Gyr. The formation redshift, $z_f = 11$, and e-folding time, $\tau = 1$, are both chosen to reproduce the observed R–z' colour of our clusters over $0.3 \lesssim z < 1$ (those of this paper, and those presented in Andreon et al. 2004a), and the typical colour of present-day ellipticals, B–$V \sim 0.95$ mag. This population is referred to as to thex spectrophotometric elliptical population. The e-folding time of the bluer track is chosen to have a present-day colour B–$V = 0.75$ mag, i.e. 0.2 mag bluer than an elliptical, as the BO definition requires (i.e. $\Delta = 0.2$ mag). We refer to this template as the spectrophotometric Sa, for sake of clarity. In agreement with BO, at $z \sim 0$ this spectral template is the appropriate one to discriminate between red and blue galaxies. However, the two tracks do not run parallel, which means that what is characterized today by $\Delta = 0.2$ mag was $\Delta > 0.2$ mag in the past (at higher redshift). This reflects the fact that at that time the Universe, and its content, were younger. The choice of a fixed Δ allows galaxies, even those with simple exponential declining star formation rates, to move from the blue to the red class, as time goes on (as redshift becomes smaller). This drift boosts the blue fraction f_b at high redshift. Because the choice of a fixed Δ allows a possible drift from one class to the other, and assuming that a redshift dependence is found for the blue fraction, does the above tell us something about the relative evolution of red and blue galaxies? It merely reflects a selection bias related to the way galaxies are divided in colour classes: a class naturally becomes contaminated by the other class. This is precisely what Weiner et al. (2005) observed.

From an observational point of view, measurements are rarely taken in filters that perfectly match B and V. Therefore, the colour cut is computed using a spectral template. The latter is usually taken from the Coleman, Wu & Weedman (1980) spectrum, i.e. for a non-evolving template. If the blue fraction is computed in such a way, then different values are found, even for a fixed galaxy sample, because a non-evolving and an evolving template only match at $z = 0$. In fact, Fairley et al. (2002) found that the blue fraction is higher if a bluer rest-frame set of filters is used. Thus, some galaxies turn out to be either blue or red depending on the selected filter set, although the two classes should be separated.

The upper solid curve in the right panel of Fig. 1 reinforces the conclusion of the above discussion, but in the observer rest frame. The solid line marks the expected R–z' colour difference, in the observer bands, for an evolving template having $\Delta(B$–$V) = 0.2$ today, i.e. considering our evolving Sa spectral template. The dashed curve illustrates the R–z' colour difference that one would incorrectly use if no stellar evolution was allowed for. It has been computed for a non-evolving Sa template. Finally, the circles show the R–z' colour difference one should derive by using non-evolving templates taken from Coleman et al. (1980), as usually done. There is a rather good agreement between the latter track and our non-evolving Sa track over a large redshift range ($0.3 < z < 0.7$). This reflects the fact that the spectra of the two templates agree with each other at $z = 0$ over a large wavelength range and that our Sa model reasonably describes (at the requested resolution) the observed spectra of Sa galaxies in the local Universe listed in Coleman et al. (1980).

To conclude, we definitively adopt an evolving Sa template to differentiate between blue and red galaxies, i.e. an evolving Δ colour cut as shown by the solid curve in the right panel of Fig. 1. Galaxies bluer than an Sa spectral template are referred to as 'blue', and those redder as 'red'. The blue fraction is therefore computed with respect to a galaxy model that quietly forms stars as our Sa model. Our choice has the advantage of focusing on galaxy evolution, instead of focusing on observational problems related to the filter choice or of assuming an unphysical universe, in which the age of the Universe

does depend on redshift, but in which the age of its content does not.

5 TECHNICAL DETAILS

Before proceeding with the calculation of the fraction of blue galaxies f_b, several additional operations need to be made, as follows.

(i) The colour red sequence is derived from the median colour of the three brightest galaxies considered to be viable cluster members, i.e. galaxies that are too blue or too bright to be plausibly at the cluster redshift are discarded.

(ii) The slope of the observed colour–magnitude relation is removed from the data. The slope is an eyeball fit to the observed colour–magnitude of galaxies in the cluster centre, in order to limit the background contribution. We measure 0.025 colour mag per unit mag at the studied redshifts.

(iii) The adopted radius that encloses an overdensity of 200 times the critical density, r_{200}, is computed from the relation

$$r_{200} = \frac{\sigma_{1D}}{H_0 \sqrt{30 \left[\Omega_m (1+z)^3 + \Omega_\Lambda \right]}} \qquad (1)$$

(Mauduit, Mamon & Hill, in preparation) where σ_{1D} is the cluster velocity dispersion. Found values are listed in Table 1.

(iv) The centre of the cluster is defined by the position of the brightest cluster member (BCM), with one exception: XLSSC 006 has two BCMs, and we took the cluster centre at the middle of the two. The adopted centre is compatible with the detected X-ray centre. Their precise location is unimportant for measurements performed within r_{200}.

(v) Galaxies redder than an Sa are referred to as red galaxies (Section 4), but how far in the red direction should we integrate the colour distribution? We adopted several cuts (including $+\infty$), and in six out of seven cases, we find no evidence for a bias in the measured f_b for any cut redder than the colour of an E $+0.05$ mag, i.e. we find no statistical evidence for a cluster population redder than the colour–magnitude sequence plus 0.05 mag. Actually, such a population is not expected from population synthesis models, because the reddest model galaxies have the colour of the red sequence galaxies. By keeping the smallest value (the colour of an E $+0.05$ mag) we maximize the signal-to-noise of the blue fraction determination, without biasing the measurement.

(vi) When selecting the background region, we choose the most representative realization of the control field: all the regions which are not associated with the target, i.e. such that $r > 2r_{200}$. The precise radius used (say $r/r_{200} > 2$ or 5) is irrelevant, because the contribution of galaxies in the cluster outskirts is negligible with respect to the number of field galaxies in our huge control area (approximately 0.3 deg^2). Other researchers prefer instead to choose the background area in regions particularly devoid of galaxies, hence unduly boosting the number of members and apparently reducing the noise in the f_b estimate.

(vii) We have verified that our galaxy catalogues are complete down to $M_V = -19.3$ mag (and fainter magnitudes), as in previous works (e.g. Garilli, Maccagni & Andreon 1999; Andreon, Lobo & Iovino 2004).

6 RESULTS

6.1 Colour–magnitude and colour distribution

The colour–magnitude relation and colour distribution of three (out of seven) clusters in our sample are presented in Andreon et al.
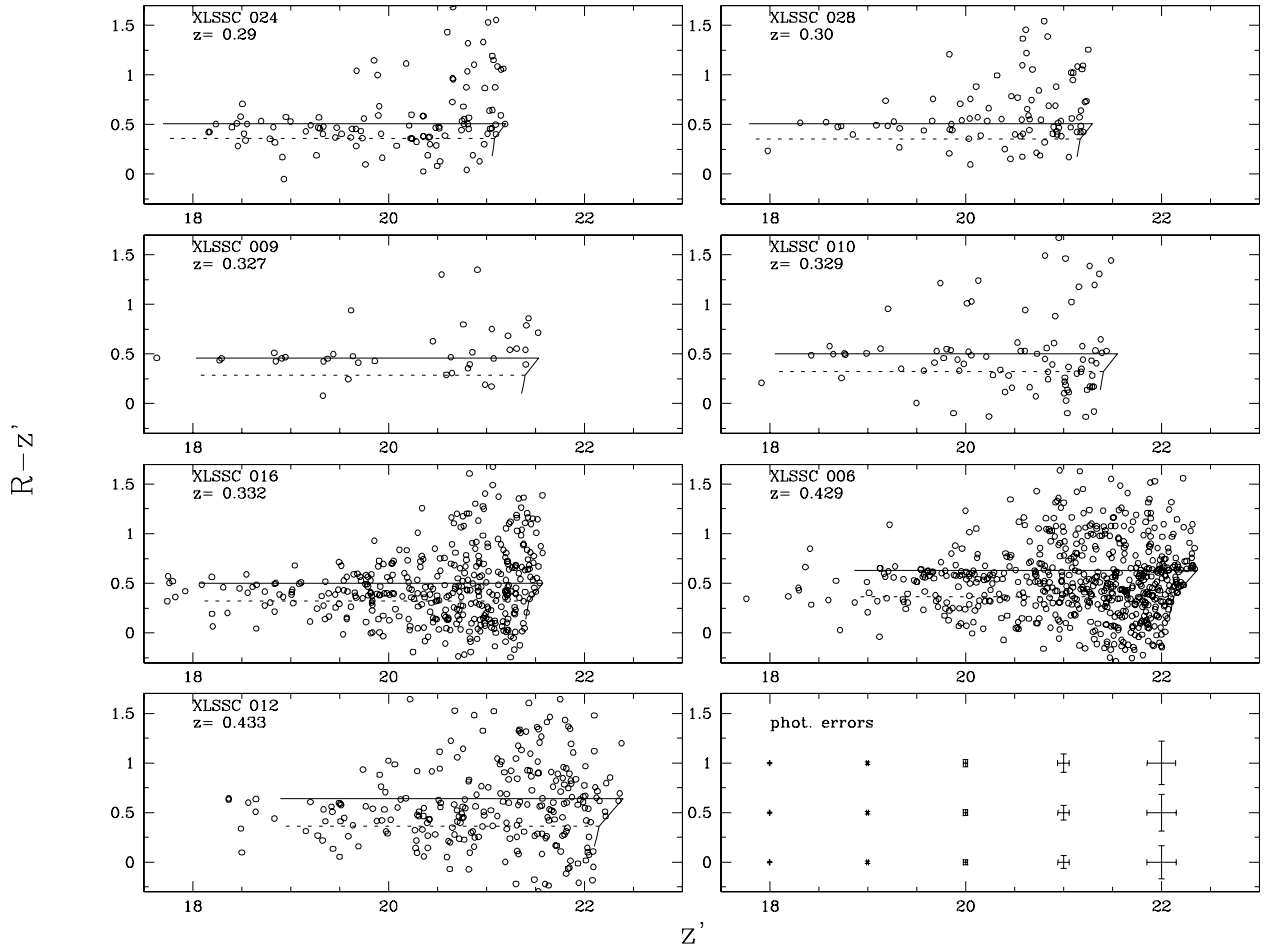
Figure 2. Colour–magnitude diagram for galaxies within r_{200}. Only galaxies brighter than the evolved $M_V = -19.3$ mag (indicated with a spline curve) are shown. Colours are corrected for the colour–magnitude relation. The solid (dashed) line marks the expected colour of an evolving E (Sa) spectral template.

(2004a), and discussed there with 15 additional clusters. Here we only want to discuss what is directly relevant for the BO effect.

Fig. 2 shows the observed colour–magnitude relation for galaxies within r_{200} (including background galaxies), corrected for the colour–magnitude slope (Section 5), and difference in seeing between the R and z' exposures (Section 2.1). The solid line marks the expected colour of the assumed spectrophotometric E template discussed in Section 4. There is a good match between the expected and observed colours of the red sequence for six out of seven cases. The red sequence of XLSSC 016 is slightly bluer (by 0.05 mag) than expected, a feature that can be better appreciated in Fig. 3. This single (out of seven), and admittedly small, offset is not in disagreement with our error estimate for the colour calibration of about $\lesssim 0.03$ mag (Andreon et al. 2004a), and therefore such a minor mismatch has been corrected for (by shifting the R–z' colour by this amount), in the f_b determination, but has been left untouched in Figs 2 and 3 to allow the reader to appreciate it. Unduly neglecting the above correction induces a bias (actually a systematic error) of 0.01 in f_b. The error bar on f_b (including everything in the error budget) turns out to be 16 times larger.

Fig. 3 shows the colour histograms of galaxies brighter than the evolved $M_V = -19.3$ mag located along the line of sight of the cluster (solid histogram) and in the control field (dashed histogram, ~ 0.3 deg^2), normalized to the cluster area. The control field is taken from the same image where the cluster is observed, and hence shares

the same photometric zero-point and quality. Therefore, any systematic photometric error largely simplifies in the blue fraction determination, because both colour distributions are shifted by the same amount (including the case of XLSSC 016).

6.2 Blue fractions for individual clusters

Table 2 summarizes our point estimate of the cluster richness, the blue fraction f_b, and its associated error, computed as described in Appendices B and C. Shortly, we introduce methods of widespread use in the statistical community, but largely unused in previous BO studies, which are more robust than traditional methods. Instead of introducing an estimator for the blue fraction and of providing a point estimate of it, which, in the long run (i.e. if we were allowed to repeat the observations a large number of times), tends to the quantity aimed to measure (the blue fraction), we compute the probability of each value of the blue fraction, given the data, using the Bayes theorem of statistics. Bayesian inference is free from logical contradictions of assigning negative (or complex) values to positively defined quantities, which affected many previous BO studies.

Richness (N_{gal} in Table 2) is computed for galaxies brighter than the evolved -19.3 mag and located inside r_{200}. Our clusters are quite poor, on average, although they show a large range of richness.

Fig. 4 shows the (posterior) probability that our clusters have a fraction f_b of blue galaxies within r_{200} assuming a uniform prior.
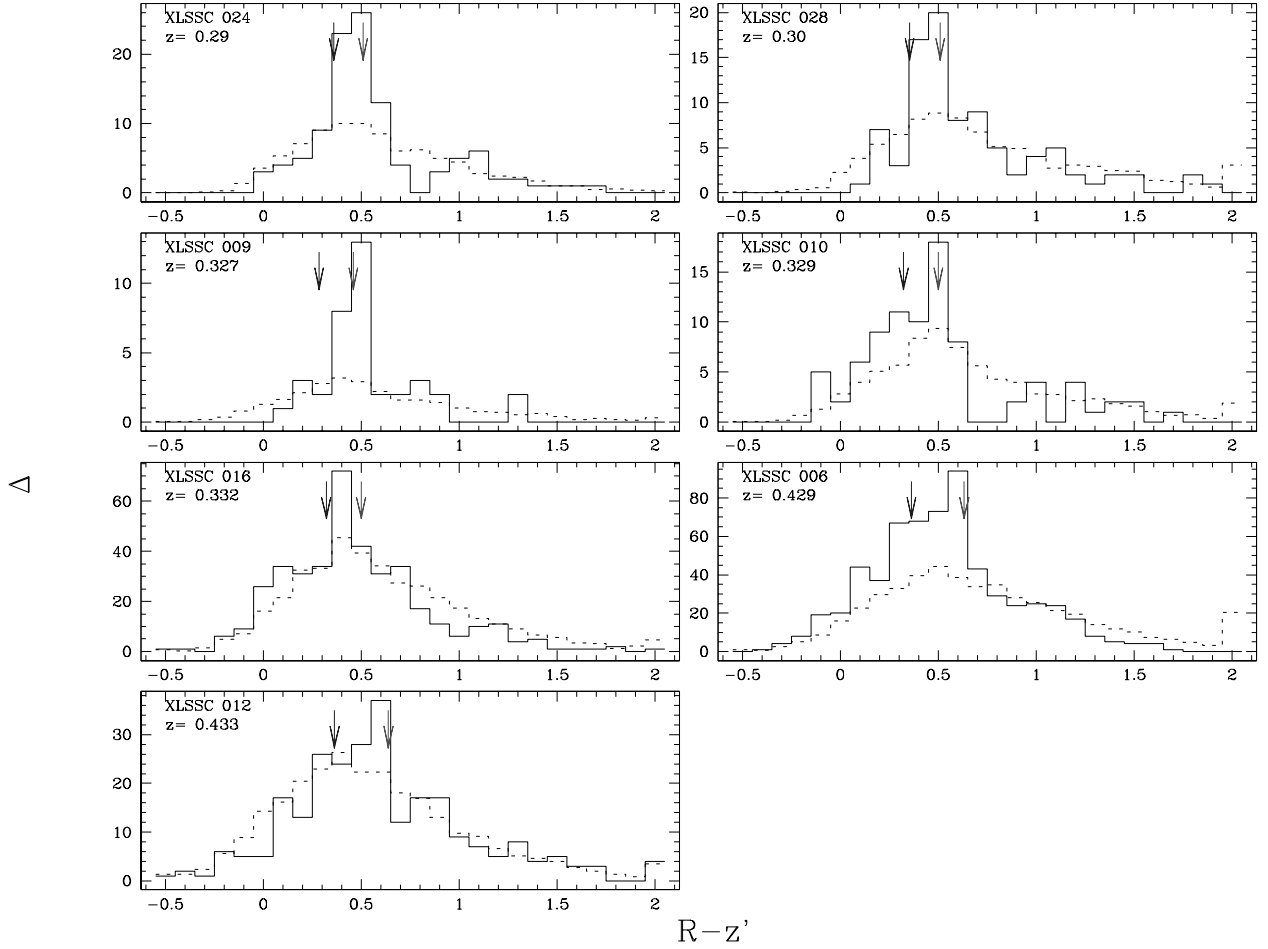
Figure 3. Colour distribution of galaxies located within r_{200} and brighter than the evolved absolute magnitude $M_V = -19.3$ along the line of sight of the cluster (solid histogram) and in the control field (dashed histogram), normalized to the cluster area. Colours are corrected for the colour–magnitude relation. The right (left) arrow marks the expected colour of an evolving E (Sa) template. Colours are binned, and consequently resolution is degraded, for display purposes only.

Table 2. Blue fractions of individual clusters for galaxies within r_{200}. N_{gal} is the number of galaxies inside r_{200} and brighter than the evolved $M_V = -19.3$ mag.

Name	N_{gal}	Error	f_b	68 per cent c.i.
XLSSC 024	24	8	0.09	[0.02,0.17]
XLSSC 028	14	7	0.06	[0.01,0.11]
XLSSC 009	9	5	0.09	[0.01,0.17]
XLSSC 010	24	8	0.51	[0.33,0.68]
XLSSC 016	51	15	0.45	[0.29,0.61]
XLSSC 006	204	21	0.43	[0.38,0.48]
XLSSC 012	8	7	0.16	[0.02,0.31]

The 68 per cent central credible intervals (errors) are shown as shaded regions. They are usually small (~ ±0.1), in spite of the fact that many of our clusters contain few members. Fig. 5 is similar to Fig. 4, but under a different assumption for the prior (an upside-down parabola in the [0, 1] range and 0 outside), in order to quantify the robustness of the results on the assumed prior. The latter prior quantifies the expectation of some readers, who believe that a BO effect exists, i.e. who believe that low values of the blue fraction are unlikely a priori. The parabolic prior encodes such a belief, not favouring low values of the blue fraction. Comparison between

Figs 4 and 5 shows that our point estimate for the cluster blue fraction (the median, which by definition falls in the centre of the highlighted region) and its error (the width of the highlighted region) are only marginally affected by the choice of the prior, if it affects it at all.

Three clusters have a blue fraction within r_{200} of about 0.4, whereas the other four clusters display a blue fraction of the order of, or less than, 0.1. More precisely, the richest clusters seem to possess the largest blue fractions. What is the statistical significance of such a relationship, shown in Fig. 6? Liddle (2004) reminded the astronomical community of the difficult problem of model selection, i.e. in our case, to establish whether existing data support a model in which the blue fraction f_b depends on σ_v. Our compared models (a constant f_b versus a linear relationship between f_b and σ_v) are nested and regularity conditions hold in our case. The likelihood ratio turns out to be $2\Delta \log \mathcal{L} \sim 6.6$ when adding one more parameter. Therefore, under the null hypothesis (a constant f_b) there is a 1 per cent probability to observe a larger likelihood ratio by adding one more parameter. Furthermore, the Bayesian information criterion (BIC) introduced by Schwarz (1978), and described in various statistical textbooks (and also in Liddle 2004) offers another way to look at the same problem, in the Bayesian framework. A value of 6 or more is regarded as strong evidence against the model with a larger value of the BIC whereas a value of two is regarded as positive evidence (Jeffreys 1961). We find $\Delta BIC = 5.8$ in favour of the model
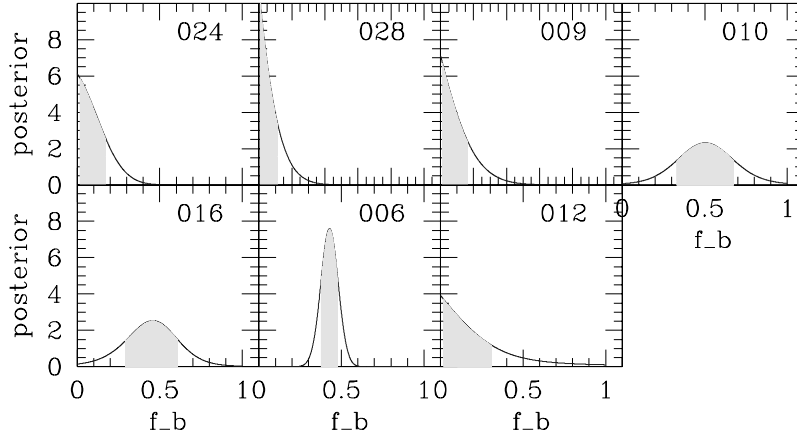
Figure 4. Probability for f_b at r_{200} assuming a uniform prior. The shaded regions delimit the 68 per cent interval (error). At its centre lies our point estimate of the cluster blue fraction. Each panel is marked by the last three digits of the cluster name.
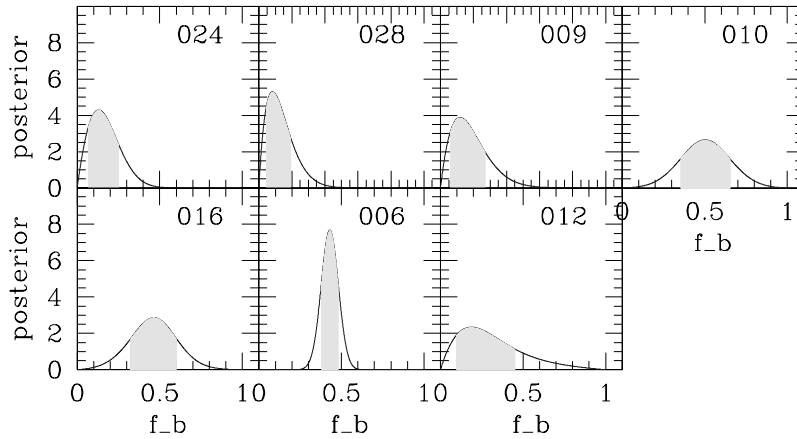

Figure 5. As Fig. 4, but for a parabolic prior.

$f_b \propto k(\sigma_v - 200)$. To summarize, there seems to be some good evidence for the existence of a linear relationship between f_b and σ_v.

However, the adopted model appears to be unphysical, because for clusters having $\sigma_v < 200$ km s^{-1}, it predicts $f_b < 0$. A more complex model is required, which perhaps flattens off at low σ_v, avoiding unphysical f_b values. At present, we consider such a model too complex, given the available set of data. Evidence for a possible correlation is recognized but it is considered far from being definitive.

Evidence for a correlation between the blue fraction and the velocity dispersion largely disappears when choosing a smaller reference radius (say $r_{200}/2$ or $r_{200}/4$), as shown in the bottom panel of Fig. 6 for $r_{200}/4$. Of course, a shallow relationship could be present, but our data do not unambiguously favour it, because the relationship, if any, is swamped by the relative importance of errors. The possible lack of a relationship between the central blue fraction and mass (measured by the cluster velocity dispersion) seems to confirm a similar lack of correlation between the cluster X-ray luminosity (a tracer of mass) and the central blue fraction (Andreon & Ettori 1999; Fairley et al. 2002).

At low redshift ($z < 0.1$), Goto et al. (2003) and Goto (2005) tentatively conclude from a larger sample of clusters that there is no evidence for a relationship between the blue fraction and the cluster mass. However, their definition of the blue fraction is different from ours, and their statistical analysis is very different (for example, Goto

et al. 2003 have observed several clusters with unphysical values for the blue fraction; see their fig. 1). Similarly, Balogh et al. (2004) find no evidence at $z < 0.08$ for a relationship between the fraction of blue galaxies inside the virial radius and the velocity dispersion, although, admittedly, fairly large uncertainties affect their results, besides another definition of what is 'blue'. It is still a matter to be investigated whether the relationship sets itself at redshifts higher than those probed by Goto et al. or Balogh et al., or whether it is masked at low redshift because of their various blue fraction definitions or because of the way the analysis is performed, or, finally, whether it is the result of a small sample at $z \sim 0.35$.

6.3 Composite sample

6.3.1 Blue fraction of the composite sample

Fig. 7 shows the (posterior) probability that the combined sample has a blue fraction f_b, computed using recursively the Bayes theorem. It is bell-shaped and narrow, which makes the blue fraction in the composite sample well determined and independent of prior: $f_b = 0.33 \pm 0.05$. The combined sample is formed by about 320 cluster galaxies within r_{200}.

What does this result mean in the presence of a possible relationship between the velocity dispersion and the blue fraction? The existence of measurements claimed to be incompatible does not
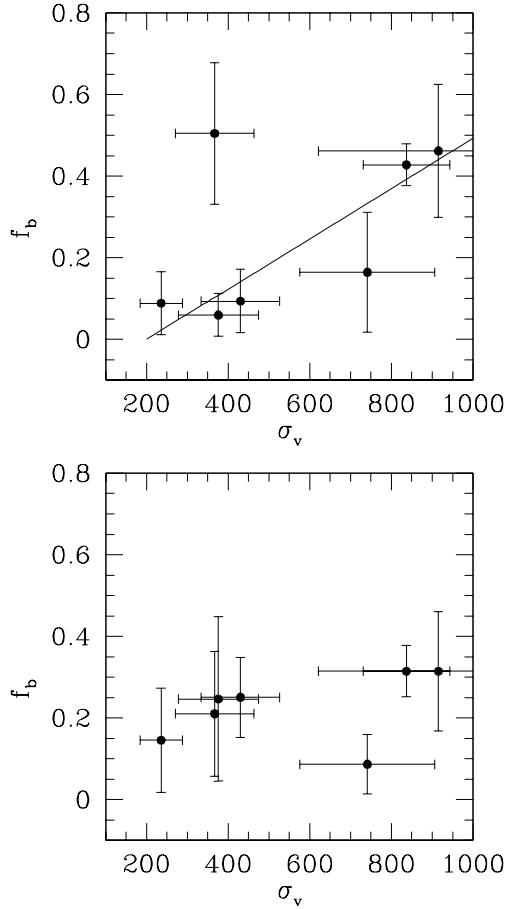
Figure 6. Relationship between cluster velocity dispersion and blue fraction within r_{200} (top panel) and within $r_{200}/4$ (bottom panel). In the top panel, the linear model favoured by the data is shown.
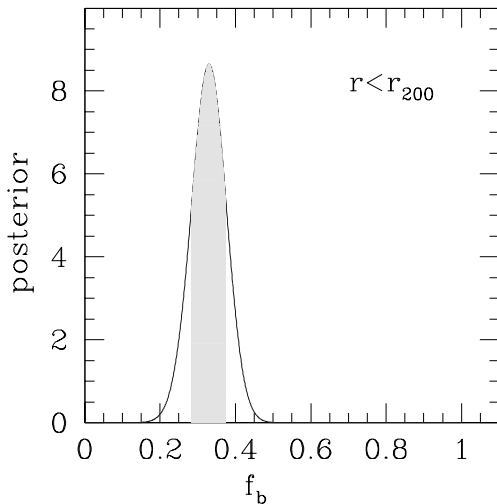

Figure 7. Constraints on f_b for the combined sample.

Table 3. Radial dependence of the blue fraction of the combined sample.

Sample	N_{gal}	Error	f_b	Error
$r < r_{200}$	321	32	0.33	0.04
$r < r_{200}/4$	136	13	0.24	0.04
$r_{200}/4 < r < r_{200}/2$	109	16	0.30	0.07
$r_{200}/2 < r < r_{200}$	78	25	0.46	0.10
$r_{200} < r < 1.5\,r_{200}$	48	25	0.55	0.14
Field	83	10	0.73	0.05

much more between each other than the uncertainties affecting the individual measurements (cf. the average post-doc salary, the average human weight or height, etc.). These averages require the sample to be a representative one, otherwise the computed average would lack its predictive power. Our sample is small, but constitutes a representative sample of clusters (Section 3).

*6.3.2 Radial dependence of the blue fraction
in the composite sample*

Different physical mechanisms are thought to operate in different environments (see Treu et al. 2003, for a summary) and thus, by identifying where the colour of galaxies starts to change, we can hope to identify the relative importance of such mechanisms. For this reason, we studied the radial dependence of the blue fraction f_b as usually done in the literature, by splitting the data in radial bins. We arbitrarily chose [0,1/4], [1/4,1/2], [1/2,1] and [1,1.5] in units of r_{200}, for simplicity. In the outermost bin we were forced to drop XLSSC 016, because $1.5r_{200}$ lies farther away than the mid-distance between XLSSC 016 and the nearest cluster to it, as seen projected on the plane of the sky, and therefore this radial bin is potentially contaminated by galaxies belonging to the other cluster. Note that its inclusion, or exclusion, in the other radial bins does not affect the derived values, and therefore our conclusions. Table 3 lists the found values.

Fig. 8 (solid points) shows that the blue fraction increases with the cluster-centric distance, from 0.24 ± 0.04 in the innermost bin, to 0.46 ± 0.10 and 0.55 ± 0.14 in the two outermost bins: galaxies at the centre of clusters are found to have a suppressed star formation (redder colours) compared to those at larger cluster-centric radii.

Have we reached the field value of the blue fraction? Using the spectrophotometry listed in COMBO-17 (Wolf et al. 2004), which encompasses 1/4 deg^2 of the *Chandra* Deep Field region, we have selected the galaxies brighter than the (same evolving) absolute magnitude limit adopted in our work, and in the same redshift range ($0.29 < z < 0.44$). There are 83 galaxies, of which 61 are bluer than an Sa evolving template. We therefore infer a blue fraction of 0.73 ± 0.05, arbitrarily plotted at $r/r_{200} = 2.5$ in Fig. 8. In the above calculation, we were forced, for lack of information, to neglect redshift errors and errors on the photometric corrections applied by the authors to compute absolute magnitudes.

The blue fraction is found to steadily increase from the cluster core to the field value.

The important point to note in Fig. 8 is that the influence of the cluster reaches large radii. There are two possible explanations for the above result. First, the mechanism affecting the galaxy colours reaches large radii. In such a case, ram pressure stripping, tidal halo
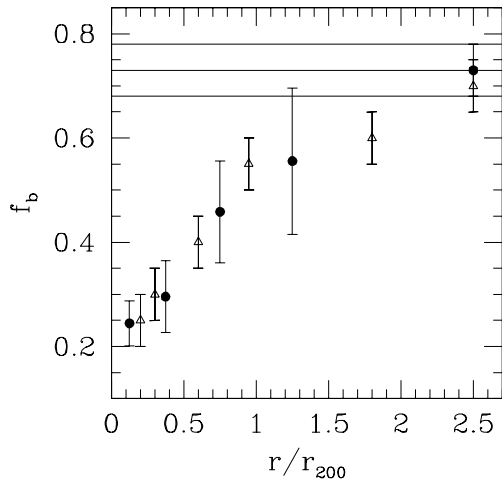
constitute an absolute obstacle when computing a sample average in the Bayesian framework, provided that the studied sample constitutes a representative one. It is in our everyday experience to compute the means of a population in which the elements differ

Figure 8. Differential radial profiles. Filled dots represent the blue fractions from our own photometry and analysis. Open triangles correspond to the fraction of galaxies with normalized star formation rates larger than one solar mass per year from Lewis et al. (2002). Our field value is arbitrarily set at $r/r_{200} = 2.5$ for display purpose.

stripping and tidal triggering star formation (just to mention a few; see, for example, Treu et al. 2003, for definitions and other examples) are ruled out as direct causes of the observed trend, because all of them are short-range mechanisms being effective in the cluster centre only.

Alternatively, the trend might be produced by a significant population of backsplash galaxies, i.e. satellite galaxies that once were inside the virial radius but now reside beyond it, as suggested on theoretical grounds by Gill, Knebe & Gibson (2005). These authors claim that about the same number of infalling galaxies and backsplash galaxies should be at $r \sim r_{200}$. Under the reasonable assumption that infalling galaxies have a blue fraction equal to the field one, and rebounded galaxies have a blue fraction equal to the central one, the expected blue fraction f_b at r_{200} should be about 0.49 [$= (0.73 + 0.25)/2$], in good agreement with the observed value, given support of the backsplash population alternative, in agreement with models and observations presented in Balogh, Navarro & Morris (2000). From a strict statistical point of view, this possibility is favoured because it provides a sharp prediction verified by the observations. The kinematical predictions of Gill et al. (2005) are also in qualitative agreement with observations of the Coma cluster: blue spirals (identified as the infalling population) have a higher velocity, relative to the cluster centre, than red spirals (identified as rebounded objects) and early-type populations (Andreon 1996).

The possible existence of a backsplash population, whose importance seems hard to quantify on theoretical grounds, requires to keep in standby our conclusion, as well other conclusions based on the (often implicit) hypothesis that the population observed at large radii is uncontaminated by rebounded galaxies (e.g. McIntosh, Rix & Caldwell 2004). For the very same reason, one should keep on hold the interpretation of the morphology–density relation (or whatever density-dependent trends in population properties, such as the strong emitter fraction), because it could be either the result of mechanisms operating at the studied density, or the result of different degrees of contamination (at different distances from the cluster centre) by the backsplash population. We are not questioning the existence of the segregation, but the way it can be interpreted.

7 DISCUSSION AND CONCLUSIONS

7.1 Comparison with previous works

The comparison of our results with others requires us to pay attention to the prescriptions adopted to define the blue fraction, to the way the cluster sample is built, and, sometimes, to the adopted statistical approach.

7.1.1 Evolution of the blue fraction

The most similar work to ours is the seminal BO paper, from which we modelled our prescriptions. By selecting a small subsample of clusters of richness similar to ours but located in the nearby Universe ($z \sim 0.02$, where BO and our prescriptions are identical) they find f_b values within r_{30}, the radius that includes 30 per cent of cluster galaxies, in the 0.02–0.19 range, with a typical error of ± 0.03. This range of values is not significantly lower, considering the various sources of uncertainties, than our central value $f_b = 0.24 \pm 0.04$, to claim that the two values are different at a high significance level, especially taking into account the fact that the BO errors are sometimes optimistically estimated (Andreon et al. 2004).

The large sample of nearby clusters of de Propris et al. (2004) matches our sample in terms of richness: we find for their sample[1] an average N_{gal} of 30 galaxies and a blue fraction inside $r_{200}/2$ of 0.17, taking into account that the blue fraction is a binomial deviate (de Propris et al. assume it to be a Gaussian and find $f_b = 0.13$). The error as a result of the sample size is negligible (0.01) because their sample is large. However, the largest source of uncertainty in their work comes from their large photometric errors (they use photographic plates). Such photometric errors induce a bias in the blue fraction, which, as discussed in Section 3.1, is difficult to correct for (Jeffreys 1938; Eddington 1940), and is neglected by de Propris et al. After accounting for minor differences in the luminosity cuts between de Propris et al. and BO and for the mentioned Malmquist bias, the estimated blue fraction within $r_{200}/2$ in the sample of de Propris et al. (2004) becomes ≈0.25, but with an error hard to quantify. Inside $r_{200}/2$ we find $f_b = 0.26 \pm 0.04$, identical to what is found in the large nearby sample of de Propris et al.

To summarize, our $z \sim 0.35$ sample matches in terms of richness the nearby samples in Butcher & Oemler (1984) and, especially, de Propris et al. (2004) and shows equal blue fractions within r_{30} and $r_{200}/2$, i.e. no BO effect is seen. It should be noted that our sample has an almost identical size and redshift distribution as the high-redshift clusters in the BO sample, and thus our lack of detection of a BO effect is not a result of a smaller or closer sample.

The compared clusters match in terms of richness, but are constructed using different selection criteria, because the low-redshift sample is an optically selected one, while our cluster sample is X-ray selected. As mention in Section 1, our X-ray selection is chosen to minimize the observational bias on f_b, and hence to derive a fair measure of the blue fraction. At low redshift, we are not aware of any reason why f_b should be biased at a fixed richness for an optically selected sample, such as those of Butcher & Oemler (1984) and de Propris et al. (2004): why should clusters of a given richness and rich in blue galaxies be over/underrepresented in cluster catalogues of the nearby Universe? Therefore, even if the selection criteria used to build the compared cluster samples are different, the comparison of the blue fractions is safe, because both cluster samples provide unbiased values of f_b.

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[1] We thank R. de Propris for giving us their blue fraction within $r_{200}/2$.

There are hints that confirm the constancy of the blue fraction at even larger redshifts. ALI04 show evidence for a low blue fraction at $z \sim 0.7$. Recently, Tran et al. (2005) have also found a low blue fraction ($f_b = 0.13$) for a cluster at $z \sim 0.6$, computed inside a cluster portion that, if not rigorously identical to that prescribed by BO, does support the non-existence of a BO effect. Both works adopted a non-evolving Δ. If an evolving Δ is used, the derived blue fraction at high redshift would even be lower than claimed, giving further support to our conclusion. ALI04 have also disproved all the reported literature evidence accumulated thus far for the existence of a BO effect, i.e. for a change of the blue fraction inside r_{30}.

All the above suggest that the fraction of blue galaxies, computed by separating the galaxies using a population formed by stars whose age increases at the same rate as the Universe age increases, does not evolve. Or, if the reader prefers, there is no systematic drift from the blue to the red classes of galaxies as the look-back time evolves, between $z \sim 0$ and $z = 0.44$.

A result similar to that depicted in Fig. 8 is presented in Lewis et al. (2002) based on nearby clusters. Our results are in qualitative agreement with theirs because we also find that the cluster affects the fraction of active galaxies up to the virial radius. Lewis et al. (2002) have studied a nearby cluster sample composed of 440 member galaxies inside the virial radius (versus our sample of 320). Fig. 8 shows that their fraction of galaxies with star formation rates, normalized to M^*, larger than one solar mass per year (triangles) compares well with our derived fraction of blue galaxies. Our error bars for their points show the expected central 68 per cent credible intervals, only accounting for sampling errors, computed by us from a straightforward application of statistics. In Lewis et al. (2002), the sample is split into classes very similar to ours and those of BO: in fact, our spectrophotometric Sa has a star formation rate, normalized to M^*, equal to their adopted threshold (one solar mass per year per M^* galaxy) if $M^* = 8.2 \times 10^{10}$ M$_\odot$, a value well inside the range of values usually observed (e.g. Blanton et al. 2001; Norberg et al. 2002). That is, what is called blue by them is also called blue by us, on average. It is not surprising, therefore, that integrating the blue profile of Lewis et al. (2002) within $r_{200}/2$ gives a blue fraction identical to that observed in the sample of de Propris et al. (2004) (0.26 versus 0.25), further supporting the similarity of the two classes (blue by colour and blue by star formation rate).

Their cluster sample has an overlapping, but different, range of masses (velocity dispersion) with respect to our sample: our richest clusters have a velocity dispersion typical of the average values of Lewis et al. (2002) clusters. However, their profile is only marginally affected, if at all, by separating clusters in (two) velocity dispersion classes (Lewis et al. 2002). Furthermore, Gómez et al. (2003) indirectly confirm that the radial profile is not too much affected by differences in cluster mass, by studying a sample of nearby clusters having velocity dispersions similar to our sample. Therefore, differences in the way the cluster samples are built seems not to affect the derived 'blue' profile.

The agreement between our blue fraction profiles and those of Lewis et al. (2002) is almost perfect. However, the studied clusters are located at quite different look-back times: the clusters of Lewis et al. (2002) are in the very nearby Universe (at $z \sim 0.07$), whereas our clusters have $z \sim 0.35$, implying a ~ 3 Gyr time difference for the adopted cosmology. As long as the separation of galaxies in classes by Lewis et al. (2002) and in our work is similar, the agreement of the two radial profiles means that there is no evolution of the blue fraction between $z \sim 0$ and $z \sim 0.35$, from the cluster centre to the field value.

7.1.2 Disagreements or different ways in interpreting the data?

Considering a much more luminous X-ray (and therefore massive) sample of clusters at intermediate redshift, Fairley et al. (2002) find an increasing blue fraction as a function of the cluster-centric distance, up to $2r_{30}$, in good agreement with the results we found over much larger cluster-centric distances. A quantitative comparison between the two pieces of work is however impossible, because there are too many uncontrolled variables that are allowed to change between these. Fairley et al. find a blue fraction $f_b \approx 0.2 \pm 0.1$, in agreement with the value we observe in the cluster centre $f_b = 0.24 \pm 0.04$. However, we believe that this apparent agreement largely arises by chance. First, Fairley et al. used a non-evolving template to separate the galaxies into red and blue classes, and find two sets of (different) values for their two sets of available colours. Secondly, they considered higher redshift than we do, by observing clusters with comparable exposure times but with smaller telescopes (2.5 m versus 4.0 m). In spite of their expected larger errors, they neglect the effect of photometric errors on their blue fraction estimates (Section 3.2). Thirdly, they do not adopt an evolving luminosity limit. Finally, a comparison of the values derived in the two works requires an extrapolation, because clusters with very different masses (X-ray luminosities) are considered.

Ellingson et al. (2001) have performed a study quite different from ours, and adopt a galaxy separation that is the same irrespective of redshift (i.e. of galaxy age), because they decomposed their spectra on non-evolving spectral templates. Their claim for a change in the population gradient is just a restatement of the fact that the blue fraction is higher everywhere in the cluster and in the field because galaxies are bluer when they are younger, i.e. it is not informative about processes running in clusters or in the field, but just informative about ageing. These authors would observe an evolution of the gradient even if galaxies were kept isolated from the surrounding environment and the infall in the cluster were fixed (i.e. no new galaxy falls in the cluster, and galaxies are kept fixed at their observed position). Their 'old population' fraction increases, going from high to low redshift, because galaxies become older, and the effect is more marked at large cluster-centric radii than in the centre, because in the cluster core the 'old population' fraction is already near to 1 and cannot take values larger than 1. Instead, we choose to reduce by one the number of parameters, removing the age dependency by using an evolving (Sa) template.

In summary, the referenced analyses do not reveal results in disagreement with our own work, although their interpretation may sometimes be different (or even opposite to ours).

7.2 Conclusions

In this paper we revise the definition used to separate galaxies into two colour classes in a way that takes into account the reduced age of the Universe at higher redshift. It is nowadays uninteresting to know whether the fraction of blue galaxies changes with redshift in a way that is different from the expectation of a model that we now know is unphysical (which has the same age at all redshifts). If the model is unphysical, there is no need to make observations to rule it out. A stellar population whose age does not change in a universe whose age instead changes, as it is supposed by using a non-evolving spectral template (or a fixed Δ, i.e. the BO prescription), is clearly non-physical. It was useful a long time ago to show that a universe with the same age at all redshifts is rejected by observations. However, nowadays we can attack a more essential question: to

know whether galaxies evolve differently from a reference evolution that is physically acceptable. Our measurements of evolution are, therefore, zero-pointed on the evolution of an object whose age increases as required by the current cosmological model. We select a spectrophotometric Sa to conform to the BO prescription in the local Universe. Effectively, this is a change in perspective: we should no longer attempt to reject an unphysical universe, in which the age of the Universe does depend on redshift, whereas the age of its content does not, but we should study whether the observed differences between the low- and high-redshift content are in agreement with differences of the Universe age at the considered redshifts.

Furthermore, we have introduced in our specific domain the tools of Bayesian inference (see appendices), dramatically improving on previous approaches that led some authors to claim that they have observed unphysical values (such as blue fractions outside the [0, 1] range or negative star formation rates). Such tools allow us to use all our data without rejecting blue fractions measured at large cluster-centric radii, where the signal-to-noise is low, contrary to previous researchers who were obliged to discard such data (or to claim that they have observed unphysical values).

The main result of this work is that we find that the cluster affects the properties of the galaxies up to two virial radii at $z \sim 0.35$.

We have measured the blue fraction of a representative sample of clusters at intermediate redshift. Indeed, our sample is a random sampling of a volume complete X-ray selected cluster sample. The X-ray selection has no cause–effect relationship on the cluster blue fraction, all the remaining parameters being kept fixed, to the best of our knowledge, and, therefore, the studied sample consists of an unbiased one (from the blue fraction point of view). Our statement should not be overinterpreted, however, because we are only sampling a portion of the X-ray parameter space. Very X-ray luminous clusters are missing in our sample because they are intrinsically rare, and clusters with fainter X-ray emission than the limiting flux are missing because they lie outside the sampled space.

Studied clusters show a variety of values for the blue fraction, when the fraction is measured within r_{200}. The variety is too large to be solely accounted for by errors. At smaller radii, instead, the blue fractions are more homogeneous. Actually, there is some evidence that the blue fraction within r_{200} increases with the cluster velocity dispersion, i.e. with the cluster mass, whereas the increase at smaller radii is much smaller, if present at all. Therefore, intermediate redshift clusters with the largest masses show the largest fractions of star-forming galaxies, when measured within r_{200}. However, the evidence is good but not definitely conclusive and still requires an independent confirmation.

The radial dependence of the blue fraction is quite shallow: it smoothly and monotonically increases from the centre to the field. The latter has been determined according to our prescriptions using COMBO-17 data.

The radial dependence (i.e. the blue fraction at every computed cluster-centric radius) is equal to that recently found in a comparable sample of clusters, but in a 3-Gyr older universe, i.e. at $z \sim 0$ (Lewis et al. 2002). The agreement between the two derived profiles (amplitude and shape), our blue fraction within r_{30} and $r_{200}/2$ and the local similar determinations (Butcher & Oemler 1984; de Propris et al. 2004), the low blue fractions at high redshift (ALI04; Tran et al. 2005), all suggest that there is no colour evolution beyond that needed to account for the different age of the Universe and of its content. The above is found to hold from the cluster core to the field value. Previous controversial evidence from the literature assumed that the Universe becomes older while its content does not, and over-

stated the significance of the evidence or compared heterogeneously measured blue fractions (as shown in ALI04).

The interpretation of the observed radial trend is complicated by the possible existence of a backsplash population. If the backsplash population represents a negligible fraction of galaxies at a given cluster-centric radius, then the large cluster-centric distance at which the cluster still produces some effect rules out short-range scale mechanisms. However, the predicted backsplash population is precisely what is needed to explain our observed fraction at r_{200}, given the fraction at the cluster centre and in the field, and also qualitatively accounts for different kinematics of galaxies having different star formation rates (blue and red spirals) in the Coma cluster. If this is the case, mechanisms efficient in the cluster centre only come into play because galaxies are affected when they reach the cluster core, and are then scattered at large cluster-centric radii where they spend much time and are observed.

The possible existence of the backsplash population does not offer us the possibility to draw a final inference about the nature and the time-scale of the processes that shape galaxy properties in clusters. The backsplash mechanism is a physical one: it affects the interpretation of measured radial (or density) trends drawn by us and other authors, and forces us to keep in hold their interpretations. However, the infall pattern turns out not to have changed during the last 3 Gyr, as measured by the identical blue fraction profiles at $z \sim 0$ and $z \sim 0.35$, in spite of apparently contradictory previous claims, based on the use of a fraction definition that has one more (uncontrolled) dependence.

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APPENDIX A: STATISTICAL INFERENCE – VELOCITY DISPERSION

Velocity dispersions and their uncertainties are computed according to statistical inference textbooks in a Bayesian framework, from the observed values of the galaxy redshifts, while accounting for measurement errors. Using a Monte Carlo simulation, we first numerically derive the likelihood of observing σ_v computed using the scale parameter introduced by Beers et al. (1990), given the observed redshifts and redshift errors. Then, using the Bayes theorem and adopting a uniform prior, we derive the probability that the cluster has a velocity dispersion σ_v, given the observed values of redshifts. The posterior, for the chosen prior, turns out to be very well described by a Gaussian.

Velocity dispersions (point estimates) and uncertainties (68 per cent central credible intervals) are quoted in Table 1 and are robust to changes of priors. Adopting a widely different prior ($1/\sigma^2$), our point estimate of the cluster velocity dispersion changes by 2–5 per cent of its uncertainty.

Derived velocity dispersions are corrected for the $(1 + z)$ effect.

Our velocity dispersions have the properties to be non-negative, and their uncertainties do not include unphysical (negative or complex) values of the velocity dispersion. While the above properties seem useless to state, it should be noted that they are non-trivial properties, because some unphysical velocity dispersions are still published.

It should be noted that, for the velocity dispersions presented here, the frequentist and Bayesian derivations of the value of the velocity dispersion turn out to be quite similar.

APPENDIX B: STATISTICAL INFERENCE – THE CLUSTER RICHNESS

The cluster richness within r_{200} is not naively derived using the common background subtraction (e.g. Zwicky 1957; Oemler 1974)

$$n(\text{clus}) = n(\text{total, cluster} + \text{field}) - n(\text{total, field}) \qquad \text{(B1)}$$

with obvious meanings for the symbols, using the observed number of galaxies, because it potentially leads to negative numbers of cluster galaxies, which is acceptable for the estimator described above, but not for the true value of the physical quantity aimed to be measured (the cluster richness). Furthermore, frequentist confidence intervals may have whatever size, including being empty or of vanishing length (as actually occurs precisely for the above expression when the right-hand side of equation B1 is negative; e.g. Kraft, Burrows & Nousek 1991). Measurements derived from equation (B1), and their confidence intervals, do not have the properties we would like richness and errors to have (for example, richness to be positive, and errors to be large when the uncertainty is large, and to become small when the uncertainty on nuisance parameters decreases, etc.). These are well known and discussed with several degrees of approximation in both the frequentist and Bayesian frameworks (Helene 1983; Kraft et al. 1991; Loredo 1992; Prosper 1998; D'Agostini 2003).

Results derived from equation (B1), when $n(\text{total, cluster} + \text{field}) \approx n(\text{total, field})$, are difficult to understand and use (say in computing averages, or when we need to propagate the uncertainty from $n(\text{clus})$ on a derived quantity). This situation occurs for one of our clusters (XLSCC 012, if equation B1 is used, but we do not use it): its richness is -2 and its confidence interval (at whatever confidence level) is empty (Kraft et al. 1991).

'If the results are to be supposed to have any relevance beyond the original data' (Jeffreys 1938), we believe that it is preferable to quote the point estimate of the cluster richness, given the data in hand, in place of the algebraic result of equation (B1). We compute the (posterior) probability that the cluster has n galaxies, and, when needed, we summarize it, quoting, as we do for the velocity dispersion (Appendix A) and the blue fraction (Appendix C), the median and the 68 per cent central interval. Specifically, we assume

a uniform prior, taking advantage of the fact that the problem is mathematically worked out by Kraft et al. (1991). We have checked that an almost identical result is obtained using a Jeffrey prior (the problem is worked out by Prosper 1998), once differences in the type of credible intervals are accounted for, i.e. that the result found is only marginally affected, if at all, by the prior choice.

It is comforting to find that XLSSC 012, which has at least 12 spectroscopic confirmed members (Table 1), has some hot emitting gas, and hence does exist and has, as all clusters of galaxies, a positive number of galaxies, a listed richness of eight galaxies within r_{200} (brighter than an evolved $M_V = -19.3$ mag), even if the (naive, but widespread) application of equation (B1) attributes to it a negative number of galaxies (-2), and an empty confidence interval.

Equation (B1) is routinely used in computing cluster luminosity functions in the presence of a background, starting with Zwicky (1957) and Oemler (1974). Andreon et al. (2005) update their use.

We conclude this section by reminding that, in both the frequentist and Bayesian paradigms, the background subtraction (marginalization) does not require that the background in the cluster line of sight is equal to the average value or equal to that observed in the control field, but only that it is drawn from the same parental distribution, contrary to some astronomical misconceptions.

APPENDIX C: STATISTICAL INFERENCE – THE BLUE FRACTION

Many blue fractions published in astronomical papers can be dramatically improved. Although, by definition, the blue fraction is hardly bounded in the [0, 1] range (otherwise part of a sample is larger than the whole sample), it is often claimed that the observed value of the blue fraction is outside the [0, 1] range (data points outside this range are present in several BO-like papers). In the presence of a background, unphysical values frequently occur. The reason is that the blue fraction is computed from

$$f_b^o(\text{clus}) = \frac{n(\text{blue, cluster} + \text{field}) - n(\text{blue, field})}{n(\text{total, cluster} + \text{field}) - n(\text{total, field})} \quad \text{(C1)}$$

with obvious meanings for the symbols. The unavoidable use of the observed number of galaxies, instead of the (unknown) true ones, in the above formula makes the result difficult to understand, for the very same reasons already discussed for the richness estimator (equation B1). The use of the observed number of galaxies in equation (C1) allows us to find negative values for the blue fraction (i.e. we would claim that there are more red galaxies than galaxies of all colours) or blue fractions larger than one (i.e. we would claim that there are more blue galaxies than galaxies of all colours), statements that are hard to defend.[2] This mainly occurs when Poissonian fluc-

tuations make background counts larger than counts in the cluster line of sight, or when there are more blue galaxies in the background than in the cluster line of sight.

Equation (C1), adopted in Postman et al. (2005), forced these authors to discard two of three of their $z > 1$ clusters in the determination of the spiral fraction. Bayesian inference allows us not to discard data, to derive estimates that never take unphysical values, and (credible) intervals that have the properties we would like errors to have. As for the cluster velocity dispersion (Appendix A) and richness (Appendix B), we compute the (posterior) probability that the cluster has a blue fraction f_b, given the observed number of galaxies in the cluster direction (total and blue) and the expected number of background galaxies (total and blue) measured over a large control field. All the mathematical aspects of the above computation have been worked out by D'Agostini (2004), who provides all requested details and the exact analytical expression for the likelihood, to be used to derive the posterior, given our data. Such a posterior may be summarized by a few numbers: the median (our point estimate of the cluster blue fraction) and the 68 per cent central credible interval (our estimate of the uncertainty), exactly as we did for the case of velocity dispersion and richness.

A trivial application of the Bayes theorem allows us to account for errors on r_{200} (because of the uncertainty on σ_v). We verified that, properly accounting for r_{200} errors, our results were unchanged, mainly because the blue fraction is a smooth and slowly varying function of r_{200}.

It is interesting to note that a reasonable constraint on f_b is achieved even for XLSSC 012, in spite of the naive expectation that, the cluster being poor (equation B1 would get -2 galaxies), and the cluster richness appearing at the denominator of equation (C1), the error on the fraction is huge, and therefore the corresponding determined blue fraction is of low quality. The correct inference takes, instead, a different approach and quantifies what is qualitatively apparent in Fig. 3: to the left of the blue (left) arrow there is no evidence for an excess of blue galaxies in the cluster line of sight. Under such a condition, how is it possible that the cluster blue fraction becomes large if almost no blue galaxy overdensity is observed? Given that almost no cluster blue galaxies are there, the cluster blue fraction is low, and the number of red galaxies sets how rich the cluster is and therefore 'how low' the fraction is.

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[2] Frequentist statisticians know how to defend unphysical values and confidence intervals which contain unphysical values, but most astronomers probably will have some problems in understanding what the numbers provided by the frequentist paradigm actually mean, and will find it hard to use them, for example for computing a mean over an ensemble.

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