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Evolutionary Studies of Galaxies at Intermediate Redshifts*

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Abstract

Photometric and spectroscopic studies of cluster and field galaxies out to redshifts of $\sim 0\cdot 5$ have provided clear evidence for strong evolution over recent epochs. The development of this picture is reviewed by contrasting and comparing the investigations of distant galaxies in rich clusters and the low density field. A common link is found in that the evolution of galaxies in *both* environments is related to short-lived bursts of star formation. The triggering mechanism for these bursts is discussed with special attention being paid to the role of galaxy merging.

1. Introduction

In the context of the topic of this workshop one might be tempted to regard the times we 'look back' to at intermediate redshifts ($0\cdot 1 \leq z \leq 0\cdot 7$) to be uninterestingly small. And yet over the last decade, galaxies at these redshifts have been the subject of quite intense interest with studies showing that this may indeed be a very special epoch in terms of galaxy evolution.

In this article I wish to review the advances made in the understanding of field and cluster galaxy evolution at intermediate redshifts, going back to a discovery which has been the primary motivation for much of the work in this field—the Butcher–Oemler (1978) effect. While this effect served to focus attention on galaxies in the *cluster* environment, parallel studies of galaxies in the field have provided a critical link in determining what role the environment might play in galaxy evolution.

This paper is divided into three sections: in the next section I will describe the work done specifically on clusters and what are, currently, the most important issues. In the following section I shall discuss the recent results that have emerged from surveys of large samples of field galaxies at similar redshifts. In the final section I shall draw together the results that have come from these two areas of study and attempt to present some overall picture as to what the relevant physical processes are in recent galaxy evolution.

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2. The Butcher–Oemler Effect and Cluster Evolution

Prior to 1978, the main thrust in studying distant galaxies had been the Hubble diagram work based on first-ranked cluster members (e.g. Gunn and Oke 1975; Kristian *et al.* 1978). The abundance of spectrophotometry and broad-band colours for such objects out to $z \sim 0 \cdot 46$ and similar data for a few galaxies beyond this, gave some hint of both luminosity and colour evolution (Spinrad 1977). However, the effects were only marginal and one was never confident in using brightest cluster galaxies as evolutionary probes that one was dealing with a 'typical' galaxy.

Butcher and Oemler (1978) embarked on a quite different approach by obtaining broad-band photometry for the cluster population as a whole. Quite surprisingly, the colour distributions they derived for two rich compact clusters at $z \sim 0 \cdot 4$ (Cl 0024+16 and 3C 295) were markedly different from those of similar present day clusters, with a conspicuous blue wing present in addition to the narrow red peak of the E/S0 population. This blue galaxy excess suggested that some component of the clusters' population had evolved very strongly [$\Delta(B - V)_{rest} \sim 0 \cdot 5$ mag] over just the last one-third of a Hubble time. Butcher and Oemler suggested that this was strong evidence for the conversion of (blue) spiral galaxies to S0 galaxies via gas–sweeping processes.

Like any new result, the 'BO effect' as it is commonly called, was received cautiously if not at times with some skepticism. There were two prime concerns: firstly, the photometric method only allows the contaminating field galaxies which lie along the line of sight to and beyond the cluster to be subtracted statistically. At the depths involved, only a small underestimation of the field component would be sufficient to explain the blue galaxy excess. Secondly, it was not clear how representative the two clusters studied by Butcher and Oemler were of the general population of distant clusters. In response to these problems, there was a considerable effort to both expand the photometric data base on distant clusters and, in more recent times, to observe spectroscopically the distant cluster populations.

(a) Photometric Follow-up

As the result of extensive photometric programmes undertaken by Butcher and Oemler (1984*a*) and Couch and Newell (1984) as well as a number of smaller studies undertaken by Mathieu and Spinrad (1981), Koo (1981) and Couch *et al.* (1985), the blue galaxy content has now been measured for some 50 clusters in the range $0 \leq z \leq 0 \cdot 6$. The data from these studies, derived largely from broad-band photographic photometry of the clusters, are plotted in Fig. 1. Two panels are presented due to the different ways in which blue galaxy fraction has been measured. The top panel shows largely the data of Butcher and Oemler (1984*a*). Their blue fraction, f_B, is simply a measure of the proportion of galaxies bluer by $0 \cdot 2$ mag in rest–frame (B-V) than the peak colour of the red E/S0 population. The bottom panel shows the data of Couch and Newell (1984); their blue fraction represents the ratio of the number of galaxies with spiral-like colours to that predicted from Dressler's (1980) [morphological mix, local density] relation for nearby clusters. Both cases show that beyond $z \sim 0 \cdot 1$–$0 \cdot 2$, most clusters are 'infected' by the BO

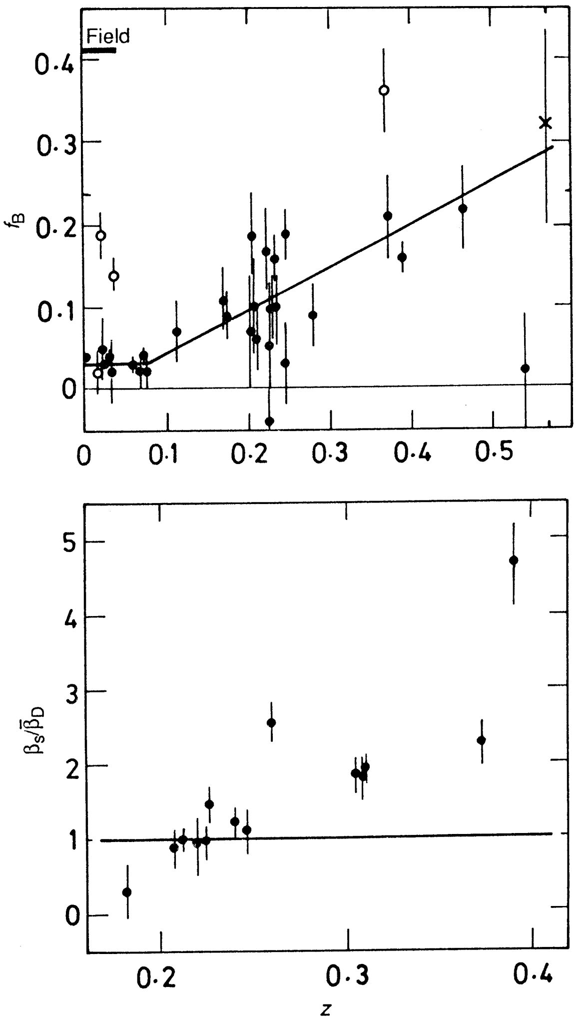

Fig. 1. Blue cluster galaxy fractions as a function of redshift. *Top panel*: Butcher and Oemler's (1984*a*) data; the cross is taken from Couch *et al.* (1985). *Bottom panel*: Couch and Newell's (1984) data. See text for details.

effect with a marginal trend for the size of the blue excess to increase with redshift (see solid line in top panel).

It is also worthwhile mentioning at this point a slightly different photometric approach taken to the problem by Couch *et al.* (1983), Ellis *et al.* (1985) and MacLaren *et al.* (1988). These authors carried out CCD-based intermediate band imaging in an attempt to obtain more detailed spectral information on the distant cluster populations than was available with the broad-band method. They used up to 7 bands spanning the uv-optical region which, in the rest-frame of the clusters, penetrated out to $\lambda \sim 2500$ Å. This allowed pseudo spectral energy distributions (SED) to be constructed for individual

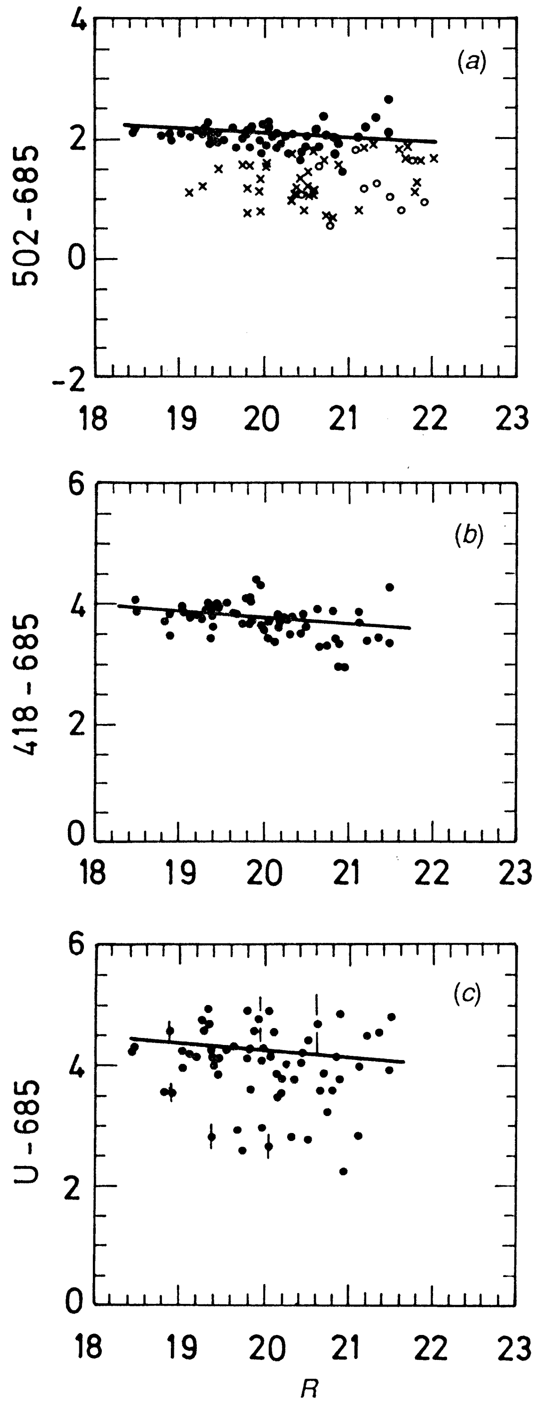

Fig. 2. Colour-magnitude diagrams for the cluster Abell 370 ($z = 0 \cdot 37$). (*a*) 502–685: all cluster members are shown; E/S0's (filled circles), spirals (crosses) and spectrally unclassified objects (open circles), (*b*) 418–685: E/S0's only, (*c*) U–685: E/S0's only with representative error bars.

galaxies which in turn could be used to locate them in the [redshift, Hubble spectral type]-plane to moderate precision. In essence this represents a poor man's approach to spectroscopy but offers gains in terms of the magnitude limits achieved ($R \sim 22$) and economy in telescope time.

As confirmed by subsequent spectroscopy, the method achieved a high level of success in discriminating between cluster and field members and in its spectral classing. It showed that the blue members in distant clusters predominantly had very flat SEDs typical of Hubble types Scd and later. Also revealed was possible evidence for a quite recent period of star formation activity in a subset of the E/S0 population. This is shown in Fig. 2 where various colour–magnitude arrays are plotted for the galaxy population in the $z = 0 \cdot 37$ cluster Abell 370. Fig. 2*a* shows the 502–685 [~(u-v) at rest] colour versus R magnitude where both the E/S0 and Sp members (as classified by the SED method) are plotted. The E/S0 population (*filled circles*) is seen to define a tight ridge line and display the well known colour-magnitude (CM) relation (Visvanathan and Sandage 1977). The spiral population (*crosses*), on the other hand, has a bluer and broader colour distribution, bounded in the red by the E/S0 sequence. Concentrating on the E/S0 component, we see in the next bluest colour 418-685 (Fig. 2*b*), the same tight sequence still remains. However, in the uv-optical colour (U-685), the sequence completely falls apart with a colour distribution which is very broad and skewed towards the blue. That this is not simply due to the photometry being swamped by random errors in the difficult U band is demonstrated by the size of the error bars shown on a number of representative points.

This observation of a subset of E/S0 galaxies in clusters appearing to be quite normal (in terms of colour and CM-effect) at wavelengths $\lambda \sim 3000$–10000 Å, and yet exhibiting an excess of light further into the uv ($\lambda \sim 2500$ Å), would appear similar to the 'uv-excess' (UVX) detected in a number of nearby elliptical galaxies (Bertola *et al.* 1982). However, Ellis *et al.* and MacLaren *et al.* point out that this occurs further into the uv ($\lambda < 1900$ Å) in the nearby objects and argue in favour of an evolutionary connection between their UVX objects and the star-burst and post star-burst galaxies which are also found in the same clusters. This is supported by evolutionary models (cf. Bruzual 1983) which show that the last remaining trace of a burst in a galaxy's spectrum is a uv excess. The significance of this result will become clearer in the discussion of the star-burst phenomenon in the remaining sections.

(b) Spectroscopic Studies

The gains made in recent years in instrumental efficiency and, in particular, the development of multi-object spectroscopic techniques has made it feasible to obtain spectra of the distant cluster populations. Thus, it has become possible to attack, *directly*, the nagging questions of cluster membership and the nature of the blue galaxies. Dressler and Gunn (1982, 1983) were the first to report results of spectroscopy of BO clusters and since that time there has been a wealth of data also published by other groups (Butcher and Oemler 1984*b*; Sharples *et al.* 1985; Lavery and Henry 1986; Couch and Sharples 1987; Mellier *et al.* 1988). The results of these studies can be summarised as follows:

(1) The photometric technique has been vindicated as a reliable means of identifying blue galaxy populations in distant clusters. In no cases could the blue galaxy excess be attributed to field galaxy contamination.
(2) The spectra of the blue members have, in general, characteristics indicative of a substantial *burst* of star formation either taking place or having just recently done so.

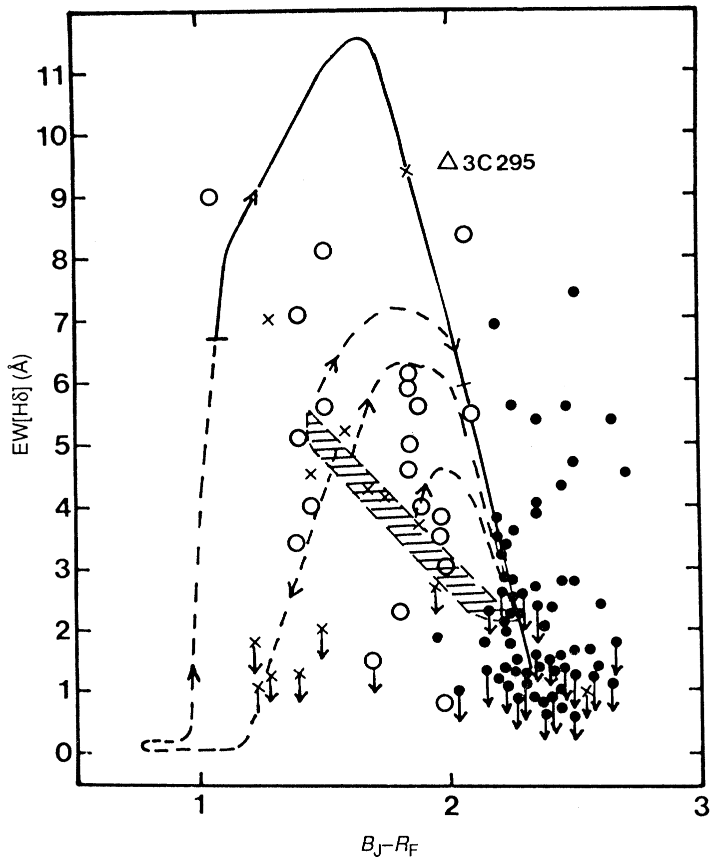

Fig. 3. Star-burst diagnostic diagram. Plotted is the Hδ absorption-line equivalent width versus observed ($B_J - R_F$) colour for the galaxy members in three $z = 0{\cdot}31$ rich clusters (Couch and Sharples 1987). See text for details.

To elaborate further on the second point, I refer the reader to Fig. 3. Here data measured from spectra obtained by Couch and Sharples (1987) for 152 galaxies in three $z = 0{\cdot}31$ clusters are presented and are well representative of the results obtained by other observers. Plotted is the equivalent width of the Balmer line Hδ as a function of broad-band colour ($B_J - R_F$). These two quantities are very good diagnostics of the recent and long-term star formation rates, respectively.

The filled circles represent the red E/S0 population. These in general have a small if negligible amount of Hδ absorption indicative of the fact that they have been dormant in star formation for at least 2–3 Gyr. There is, however, a small subset of objects which have quite large Hδ absorption (EW[Hδ] ~ 4–8 Å) and yet in all other respects are indistinguishable from the other galaxies classified as E/S0's. There is a parallel here with the UVX objects found by Ellis and co-workers, and indeed Couch and Sharples found that the spectra of the Hδ-strong objects could be matched with that of a burst model seen at late times (1–2 Gyr after the burst ended) which also suffers some internal reddening.

The emission line objects found in the clusters are denoted in Fig. 3 by crosses and not surprisingly they are all blue ($B_J - R_F < 2 \cdot 0$). They fall into two distinct areas on the diagram: One group coincides very closely with the sequence of increasing Hδ strength with decreasing (bluer) colour defined by nearby spiral galaxies and shown in the diagram as the cross-hatched area. It is concluded that these objects are the distant counterparts of nearby spirals; as a class, however, they are in a minority. The other group forms a clump at the bottom left of the plot, all being very blue and having their Hδ lines emission-filled. Indeed they have a very weak absorption-line spectrum symptomatic of an underlying component of very hot stars. They also have mild to strong [OII] and [OIII] emission.

Before considering what these latter objects might be it is helpful to discuss the remaining objects in Fig. 3. These are the objects represented by the open circles which have no emission but are conspicuous by their moderate to strong Balmer (Hδ) absorption lines. This type of object was first discovered by Dressler and Gunn (1982, 1983) in their study of the 3C 295 cluster and was labelled by them a 'post-starburst' galaxy because its spectrum could only be reproduced by the addition of an A-type stellar spectrum [representative of a young (~1 Gyr) population] to that of an old population (e.g. E galaxy spectrum).

This notion of a burst of star formation being responsible for the galaxies' blue colours and spectral characteristics was explored more fully by Couch and Sharples. They computed the 'life cycles' for a variety of burst models using the evolutionary code of Bruzual (1983) linked to the high resolution stellar spectral library of Jacoby *et al.* (1984). One such track representative of a 1 Gyr burst that takes place in a galaxy with ongoing star-formation (i.e. a spiral) and which converts 30% of the galaxy mass into stars is shown in Fig. 3. Prior to the burst it is located in the spiral sequence; upon commencement of the burst it rapidly descends (see dashed line) to the region of the diagram occupied by the bluest emission line galaxies. At this point the model reproduces very well the spectrum of these galaxies, with weak absorption lines, strong [OII] and [OIII] emission and emission line filling of the Balmer lines. A reasonable conclusion then is that these galaxies have been caught in the early stages of a star burst.

After ~0·5 Gyr, stars of spectral type A and later have been produced in sufficient numbers to overwhelm the hotter (ionising) OB population in terms of their contribution to the galaxy light and an increase in Balmer line strength is seen with little change in colour. This trend continues after the burst has finished (where the dashed line changes to a solid line) and does so for another $\sim 0 \cdot 5$ Gyr before a peak in the Hδ absorption is reached and the galaxy then begins a slow decline towards smaller Balmer absorption and redder colours. The ability of the model spectra, especially in the 1 Gyr period after the completion of the burst, to duplicate the strong Balmer absorption, continuum shape and broad-band colours of this component of the blue galaxy population provides even stronger confirmation of Dressler and Gunn's original claim of them being post-starburst galaxies. The size of the bursts (fraction of galaxy mass converted to stars) required to explain the distribution of points in Fig. 3 ranges from as low as 3% to as high as 40%.

The identification of the BO effect as being a star-burst phenomenon raises the important question of what triggers the bursts. Are the bursts being set off by some internal clock or, as would seem more likely, are they related to the environmental pressures acting in rich clusters? Two ideas commonly discussed in the literature along the latter lines have been (i) *infall*—where gas rich galaxies are falling into clusters and the ram pressure they experience causes their cold gas clouds to collapse and start forming stars, and (ii) *interactions/mergers*—where star formation is induced by galaxies either coalescing or having close encounters. However, it is appropriate that discussion of these be postponed until another key observation is mentioned: the evolutionary behaviour of galaxies in the field.

3. Field Galaxy Evolution

In an analagous way to photometric colour information having been fundamental to the discovery of evolutionary effects in clusters, galaxy number–magnitude counts have laid the foundation for studies of field galaxy evolution. In combination with careful modelling based on a detailed knowledge of the properties of nearby galaxies, they provide a quantitative measure of evolution out to redshifts of $z \sim 0 \cdot 5$ and beyond (e.g. Shanks *et al.* 1984).

Number counts have mostly been derived from Schmidt and 4m prime-focus plates, although in more recent times CCD detectors have been employed (for a review see Ellis 1990). Although there are some significant variations in the absolute numbers of galaxies seen from field to field and also between different workers, two results common to all studies are (i) the *slope* of the number-magnitude count relation is steeper than that of the canonical no-evolution prediction, and (ii) where colour information is derived, there is a monotonic trend towards bluer colours at fainter limits. It is tempting to interpret these two results as evidence for evolution in field galaxies over recent epochs but as cautioned by Kron (1983) they could equally well be attributable to a population of very low luminosity nearby dwarf galaxies.

In an attempt to distinguish between these two possibilities, several groups have undertaken spectroscopic surveys of faint field galaxies. Samples have in general been selected in the blue where the observed counts show the biggest deviation in slope from the no-evolution model. Starting at $B_J \sim 20$ where the deviation first starts to appear, increasingly fainter magnitude slices have progressively been covered: $20 \leq B_J \leq 21 \cdot 5$ (Broadhurst *et al.* 1988; hereafter BES), $20 \leq B_J \leq 22$ (Koo and Kron 1988), $21 \cdot 5 \leq B_J \leq 22 \cdot 5$ (Colless *et al.* 1989), and $22 \cdot 5 \leq B_J \leq 23 \cdot 5$ (Peterson *et al.*, personal communication).

The key discriminant in distinguishing between different evolutionary scenarios from magnitude limited field galaxy samples is the observed redshift distribution. If there had been higher levels of star formation in the past thus rendering galaxies at this epoch brighter and bluer, then one would expect to see a high redshift tail in the redshift distribution. Alternatively, if these faint samples are dominated by a population of nearby dwarf galaxies, then a low redshift ($0 < z < 0 \cdot 1$) peak should be observed. Interestingly, in the above studies, neither of these components were seen! Instead, the redshift distributions matched very closely that expected in the no-evolution case.

This result left workers with a dilemma—how could the high slope of the number counts be reconciled with a non-evolved redshift distribution? BES explored a number of avenues in an attempt to resolve this problem. The changes required in the properties of local galaxies for the no-evolution predictions to match the observations were examined but found to be too severe to be seriously contemplated. They also found there was no way out with all evolution taking place at very early times, since to get the galaxy counts high enough at $B_J \geq 20$ one would have to make the redshift of formation sufficiently low (<5) that a hump would be expected in the number–magnitude relation at $B_J > 24$. The deep CCD counts rule this out. There was no choice but to consider other, albeit non-conventional, forms of evolution.

Inspection of the spectra of the faint field galaxies reveals a much higher incidence of emission line objects than in brighter samples (e.g. Peterson *et al.* 1986). Indeed in the BES sample, the [OII]λ3727 line is present in 80% of the objects with a marked shift in the equivalent width distribution (cf. the nearby surveys) towards higher (EW > 20 Å) values. BES also noticed that these objects had a number–magnitude slope sufficiently steep to explain the overall slope of the counts in the observed magnitude range. The strong [OII] emission suggests objects with vigorous star formation and if one looks at their absorption-line spectrum there is a striking similarity with Couch and Sharples' (1987) 'bursting' cluster galaxies which occupy the bottom left hand corner of Fig. 3 (see Section 2*b*). It would appear then that the objects responsible for the excess counts at faint magnitudes are galaxies undergoing strong *bursts* of star formation.

Can we have star bursts occurring at these epochs in the field without a high redshift tail being observed in the redshift distribution? BES pointed out that the burst models which successfully fit the spectra of these star-burst galaxies indicate that the amount these objects would have brightened during the burst is as much as $\Delta B_J = 2 \cdot 2$ mag. A computation of the absolute magnitudes these galaxies would have had in their quiescent state reveals that they are mostly intrinsically faint galaxies ($M_B > -20$) which, prior to the burst, would have been fainter than the apparent magnitude limit of the sample. This amounts to a form of evolution which is *luminosity dependent*; rather than galaxies of all intrinsic brightnesses evolving by the same amount (i.e. the general evolution picture), it appears that only those which are intrinsically faint do so in the form of a short-lived burst. BES demonstrated that evolution of this kind successfully explained *simultaneously* both the number–magnitude slope and the observed redshift distribution.

4. Discussion

The evolutionary studies of galaxies in the diverse environments of rich clusters and in the general field have, quite remarkably, yielded very similar results. It is apparent that there is a common mechanism responsible for the apparent evolution in both cluster and field samples over the last 5–7 Gyr and that is the occurrence of strong but short-lived bursts of star formation. The field galaxy studies indicate that these are occurring predominantly in intrinsically faint galaxies; a check on the predicted quiescent luminosities of the burst galaxies in clusters indicates that they too are faint with magnitudes well below M^*.

This parallel between cluster and field evolution argues against the *global* environment (i.e. cluster, field or group) being of any relevance in determining a galaxy's star formation history. There was an additional hint of this in the study of Couch and Sharples (1987) where they found their three clusters to have almost identical blue galaxy populations even though the richness, velocity dispersion and binding mass of the clusters varied by a factor of three. This leads me to suggest that perhaps what is of most relevance is the *very local* environment a galaxy finds itself in—that is, the number of close neighbours a galaxy has. Indeed, Dressler (1980) has shown that it is this property that is fundamental to the environmental dependence of morphological mix.

A question still left unanswered is: what is the mechanism which triggers the bursts of star formation in the distant galaxies? While infall (see Section 2*b*) may explain bursts in some cluster galaxies, it does not provide a general explanation. The idea of local environment being important lends itself naturally to the picture of mergers and interactions. There is clear evidence from a number of studies (e.g. Dressler and Schectman 1988) that galaxies are quite often located in physically associated groups or sub-clumps both within clusters or in the field, where conditions for mergers are favourable (small crossing times and low velocity dispersion). Hence the traditional arguments against merging in clusters (velocity dispersion too high) or in the field (density too low) do not always apply. The recent high quality CCD images obtained by Lavery of the blue galaxies in distant clusters (as reported by Quinn 1990, present issue p. 135) provide exciting new *direct* evidence for merging taking place in the cluster environment. The tendency for shell galaxies (Malin and Carter 1983), which are prime candidates for merger products (Quinn 1984), to be found out of clusters provides circumstantial evidence that merging is an important process in the field as well. In this context it is interesting to note that the shell galaxies have spectra predominantly of the post-starburst type (Carter *et al.* 1988).

Clearly there are a number of details related to this picture of mergers being a trigger for the star-bursts which need to be worked out. Why, for example, were the last 3–5 Gyr such a special epoch in this regard? A challenge to *n*-body simulations of the growth of large scale structure in the universe will be to show that mergers were more highly favoured in *all* environments over this period. Observationally, the results of imaging programmes such as Lavery's will be watched with much interest. Researchers also patiently await the launch of the Hubble Space Telescope. Its high spatial resolution imaging capability will at long last provide a crucial missing link in the study of evolving galaxy populations—information on their *morphology* and the location of their star forming regions. This should provide the spur to another very active period of investigation just as the Butcher and Oemler discovery did over a decade ago.

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