The elliptical colour-magnitude relation as a discriminant between the monolithic and merger paradigms: the importance of progenitor bias

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15 December 2003

ABSTRACT
The colour-magnitude relation (CMR) of cluster ellipticals has been widely used to constrain their star formation histories (SFHs) and to discriminate between the monolithic and merger paradigms of elliptical galaxy formation. We investigate the elliptical CMR predicted in the merger paradigm by using a ΛCDM hierarchical merger model. We first highlight sections of the literature which indicate that the traditional use of fixed apertures to derive colours gives a distorted view of the CMR due to the presence of colour gradients in galaxies. Fixed aperture observations make the CMR steeper and tighter than it really is. We then show that the star formation history (SFH) of cluster ellipticals predicted by the model is quasi-monolithic, with over 95 percent of the total stellar mass formed before a redshift of 1. The quasi-monolithic SFH produces a predicted CMR that agrees well at all redshifts with its observed counterpart once the fixed aperture effect is removed. More importantly, we present arguments to show that the elliptical-only CMR can be used to constrain the SFHs of present-day cluster ellipticals only if we believe a priori in the monolithic collapse model. It is not a meaningful tool for constraining the SFH in the merger paradigm, because a progressively larger fraction of the progenitor set of present-day cluster ellipticals is contained in late-type star forming systems at higher redshift, which cannot be ignored when deriving the SFHs. Hence, the elliptical-only CMR is not a useful discriminant between the two competing theories of elliptical galaxy evolution.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – galaxies: fundamental parameters

1 INTRODUCTION
Evolution with redshift of fundamental physical relations can provide robust constraints on the epoch of formation and subsequent evolution of early-type galaxies. The apparently universal relationship between colour and luminosity of elliptical galaxies, usually referred to as the colour-magnitude relation (CMR), was first established by Sandage & Vishvanath (1977), although the correlation between these two quantities had been demonstrated before (e.g. Baum 1959; de Vaucouleurs 1961; McClure & van den Bergh 1968). The CMR has been widely used as a discriminant between the two competing theories of early-type galaxy evolution, the monolithic collapse model (e.g. Eggen et al. 1962, Tinsley 1972, Larson 1974, Chiosi & Carraro 2002) and the hierarchical merger model (e.g. Kauffmann et al. 1993, Somerville & Primack 1999, Cole et al. 2000, Hatton et al. 2003, Khochfar & Burkert 2003).

A comprehensive study of the CMR, using photometric data based on CCD observations of the nearby Virgo and Coma clusters, was first undertaken by Bower, Lucey & Ellis (1992, hereafter BLE92). Their results showed a remarkably small scatter about the mean relation. Their interpretation of the results, in the context of the monolithic collapse model, was to attribute the slope of the CMR to a variation in mean metallicity with luminosity and to attribute the small scatter to a small age dispersion between galaxies of the same size. They concluded that the epoch of formation of elliptical galaxies must be at z > 2. Subsequent studies of the CMR extended the BLE92 results to intermediate redshifts (0 < z < 1) and...
showed that there was no detectable evolution of the slope and scatter with time (e.g. Ellis et al. 1997; Stanford et al. 1998; Gladders et al. 1998; van Dokkum et al. 2000). The results from these studies were interpreted as confirmation of a high-redshift formation epoch of cluster ellipticals followed by passive evolution to present day.

However, other studies have indicated that the key characteristics of the CMR (slope and scatter) that were derived by these authors needed to be revised. Elliptical galaxies commonly display radial colour gradients (e.g. de Vaucouleurs 1964; Sandage & Vishvanath 1978; Franx et al. 1988; Peletier et al. 1990), being redder at their cores than at the outskirts. Galaxy colours in the majority of these CMR studies were derived using fixed apertures which, given that a galaxy’s intrinsic size may vary, meant sampling different portions of different galaxies, making the derived CMR less meaningful (Scowcroft 2001). Attempts to correct for this effect had been made before. Sandage & Vishvanath (1978) corrected their colours to a constant fraction of a galaxy’s isophotal radius but isophotal radii contain variable fractions of a galaxy’s light, so this correction does not alleviate the problem. Similarly, theorists have attempted to convert total magnitudes given by their models to fixed aperture values using mean colour gradients (e.g. Kodama et al. 1998; Kauffmann & Charlot 1998). Unfortunately, the large intrinsic scatter in the amplitude of colour gradients in galaxies of all luminosities (e.g. Peletier et al. 1990) makes this correction unrealistic.

The fixed-aperture bias can be avoided by calculating colour indices from total magnitudes or at least by considering an identical fraction of light in each galaxy. Scowcroft (2001) showed that re-computing colours over the effective radius (radius which contains half the galaxy’s light) for the BLE92 galaxies causes the apparent slope to decrease significantly from $-0.082 \pm 0.008$ to $-0.016 \pm 0.018$, a value which is consistent with a zero slope. In addition, the scatter increases from 0.035 to 0.136, due to the large intrinsic scatter in the colour gradients. Shallow slopes had been reported before by Frinchaboy & Simard (1996) who used colours similarly derived at effective radii and by Floc & Rocca-Volmerance (1994) who used total magnitudes and colours. A recent work using 9000 elliptical galaxies selected from the Sloan Digital Sky Survey (Bernardi et al. 2003) adds weight to these results and also indicates that fixed-aperture ($g-r$) colours produce steeper CMRs, with the relation almost completely absent if colours are defined using total magnitudes. Scowcroft (2001) noted that the flatter and larger values for the slope and scatter respectively meant that there may not be as significant a colour-luminosity correlation as had previously been thought and that events such as mergers or secondary starbursts could be accommodated into star formation histories of cluster ellipticals.

The revisions to the characteristics of the CMR, coupled with evidence for morphological evolution among cluster galaxies suggests that formation mechanisms of cluster ellipticals are at least not uniquely monolithic. Although approximately 80 percent of galaxies in the cores of present day clusters have early-type morphologies (Dressler 1980), a higher fraction of spiral galaxies have been reported in clusters at $0.3 < z < 0.8$ (e.g. Butcher & Oemler 1984; Dressler et al. 1997; Couch et al. 1998; van Dokkum et al. 2000), along with increased rates of merger and interaction events (e.g. Couch et al. 1998; van Dokkum et al. 1999; Kauffmann et al. 1999) suggested that only approximately one-third of early-type galaxies in the Canada-France Redshift Survey were fully formed and evolving passively. Franceschini et al. (1998) found a remarkable absence of early-types galaxies at $z > 1.3$ in a K-band selected sample in the Hubble Deep Field (HDF) and suggested that galaxy merging may play an important part in the formation of early-type systems. These results strongly suggest that early-type galaxies in nearby and distant clusters may have been formed from late-type progenitors (e.g. Butcher & Oemler 1984; Dressler et al. 1997) and highlight the possible if not essential role of merger and interaction events in the formation of early-type galaxies. In particular, if the merger paradigm is correct then late-type progenitors of the present-day cluster ellipticals must be included in any method (e.g. the CMR) employed to determine their SFHs. Excluding these late-type progenitors would produce a distorted view of their formation histories (progenitor bias), a point explored by van Dokkum & Franx (2001).

Given the accumulating evidence for formation of early-type galaxies from star-forming progenitors at fairly recent epochs, a number of authors have successfully reconciled the observed CMR with galaxy merging models (Kauffmann & Charlot 1998; Bower et al. 1998; Shiya & Bekki 1998; van Dokkum et al. 1998). Apart from Kauffmann & Charlot (1998), these studies have not involved a fully realistic semi-analytical galaxy formation model which incorporates the important effects of galaxy merging on the chemo-photometric evolution of galaxies. One of our aims is to extend these studies by applying an ΛCDM hierarchical merger model to study the CMR from low to high redshift.

We begin our study by discussing the comparative effects of age and metallicity in determining the model $(U-V)$ CMR at present day and tracing the bulk SFHs of cluster ellipticals as a function of redshift. We briefly discuss model parameters that change the characteristics of the present-day CMR. We then explore the predicted evolution of the CMR to high redshifts, compare with existing observational evidence and, in particular, quantify the effect of progenitor bias. However, our focus is not simply on reconciling the observed CMR with the hierarchical merger picture. Using our analysis of progenitor bias, we present arguments to show that the commonly used elliptical-only CMR, even when it is derived using fixed light fractions (c.f. Scowcroft 2001), can only be used to constrain the SFHs of cluster ellipticals if we believe a priori in a monolithic collapse model. It is not a meaningful method of constraining the SFH in the hierarchical merger picture. Hence it is also not a useful discriminant between the two competing theories of galaxy evolution.

2 PROPERTIES OF PRESENT-DAY CLUSTER ELLIPTICALS

We begin by exploring the present day CMR predicted by our model. The model we use is GALICS, which combines large scale N-body simulations with simple analytical recipes for the dynamical evolution of baryons within dark matter.
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Figure 1. The model colour magnitude relation at z=0. TOP: CMR sequence with a linear least-squares fit (dotted line) and a progressive one-sigma fit to the sample. The error bars indicate the local spread of points about the best-fit relation. SECOND FROM TOP: CMR as a metallicity sequence. THIRD FROM TOP: CMR as an age sequence. BOTTOM: Cluster ellipticals split into their individual clusters.

Figure 2. Intra-cluster scatter as a fraction of the total scatter. The sizes of the symbols are proportional to the number of ellipticals in the cluster. The highest elliptical occupancy in a cluster is 48.

Figure 3 shows the variation in the mean ages and metallicities of the model cluster ellipticals with V-band luminosity. We also show the age-metallicity parameter space for these model galaxies in Figure 4. We should note here that the metallicity resolution in the model is low, with stellar mass resolved only into five metallicity bins in the range $-1.3 < [m/H] < 0.5$. We have indicated the maximum average metallicity error for model galaxies with sub-solar and
super-solar metallicities in Figure 3 by considering the half-widths of our metallicity bins. The resolution in age, by comparison, is extremely good (0.1 Gyr), as indicated by the small age error bars.

The model predicts a gradient both in the age-luminosity and metallicity-luminosity relations, so that larger ellipticals are both older and more metal-rich. We note first that contrary to previous hierarchical merger models (e.g. Kauffmann & Charlot 1998), higher mass (luminosity) ellipticals are predicted to have larger mean ages, in agreement with observation evidence (see e.g. Trager et al. 2000a,b; Caldwell et al. 2003). The difference arises due to the implementation of AGN feedback in GALICS. Current understanding of cooling flows in clusters is poor. Models suggest that if large inflows of cold gas are allowed at the centre of virialized DM haloes, it is impossible to prevent a large fraction of this material from forming stars, which are unfortunately not observed at the present epoch. To prevent this, one has to reheat or keep gas hot in massive DM haloes. Various authors have tackled this problem in different ways. Kauffmann et al. (1993), for instance, prevented cooling from taking place in DM haloes with circular velocities of 350 km/s and above. GALICS takes advantage of the observed correlation between AGN and bulge mass (Magorrian et al. 1998) and assumes that AGNs are efficient enough to completely halt cooling flows as soon as the bulge which harbours them reaches a critical mass of $10^{11} M_\odot$. This coupling between AGN feedback and bulge mass prevents star formation early enough in large elliptical galaxies to allow them to grow solely through mergers of gas-poor progenitors and thus reverses the age-metallicity trend found in previous hierarchical models. Thus, although galaxies with a larger mass experience their last merging events at a later time than their less luminous counterparts, the small gas fraction at these last-merger epochs prevents any substantial production of young stars from merger driven starbursts. Therefore, although more massive galaxies are dynamically younger based on their merger record, their stellar populations are, nevertheless, older. The average predicted age of a cluster elliptical is approximately 9.8 Gyrs and the scatter in age increases towards the low mass end, in agreement with recent observational studies in clusters such as Virgo (Caldwell et al. 2003). The average metallicity is approximately solar and the gradient in metallicity is modest, also in general agreement with recent spectroscopic studies of nearby cluster environments (Caldwell et al. 2003).

A comparison with simple stellar population (SSP) models (Yi et al. 1997) shows that roughly half of the CMR slope is generated by the age-luminosity gradient, with the rest attributable to the metallicity-luminosity gradient in the model sample. Clearly, the age and metallicity gradients complement each other in this model, in contrast to Kauffmann & Charlot (1998) where the anti-correlation between age and luminosity required a large compensating metallicity gradient (generated through high metal yields) to produce a CMR that was consistent with the BLE92 observations.

Figure 4 presents the bulk cumulative SFH of the model cluster ellipticals. The SFH is shown both split into the five GALICS metallicity bins and considering all stellar mass. The cumulative SFH shows that less than 5 percent of the total stellar mass (solid bold line) was formed after $z = 1$, with 75 percent and 48 percent already in place at $z = 2$ and $z = 3$ respectively. The bulk SFH is quasi-monolithic because the low cold gas fraction at low redshifts ($z < 1$) means that merger-driven star formation does not produce substantial amounts of stellar material. This enables the model elliptical CMR to maintain its slope and small scatter up to high redshifts (Section 4).
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3 MODEL PARAMETERS THAT AFFECT THE PRESENT-DAY CMR

There are certain key parameters in the model that affect the age and metallicity of the model galaxies and thus have an impact on the slope, scatter and absolute colour of the predicted CMR. A discussion of these model parameters is necessary not only to elucidate their effect on the CMR but also because the actual setup we use in this study is slightly different from the reference model given in Hatton et al. (2003). The setup has been altered firstly to make some corrections to the metallicity of fresh gas injected into DM haloes and secondly to bring the predicted metallicities of the model galaxies in agreement with current observational evidence. Table 1 summarises the changes in the characteristics of the CMR due to variations in these parameters. In the subsequent sections we present an explanation of the parameters and the values used in this study.

### 3.1 Baseline metallicity

The reference model in GALICS adds pristine i.e. metal-free gas to DM haloes when they are identified. However, the haloes are not identified until they achieve a threshold mass of $10^{11} M_\odot$. In reality, early population II stars would already have polluted the ISM in the time that it takes for such halo identifications to take place. Hence, the gas in the haloes should not be pristine but slightly polluted. Chemical enrichment models (e.g. Devriendt et al. 1999) suggest that this pollution should be of the order of $0.1 Z_\odot$. Hence, we use this value as a baseline metallicity for fresh gas injected into DM haloes in the model. The baseline metallicity only affects the final metallicities of the model galaxies. It has a negligible effect on the CMR but slightly affects the absolute colour of the cluster sample.

### 3.2 Threshold black hole mass and IMF

Another parameter that affects the metal input into the ISM, and therefore the average metallicity of the stellar population, is the threshold mass at which a star becomes a black hole (BH). This is still poorly understood, but estimates suggest masses around $50 \pm 10 M_\odot$ (Tsujimoto et al. 1997), based on a combination of local stellar [O/Fe] abundances and chemical enrichment analysis. We have used a threshold black hole mass of $60 M_\odot$ in this study.

Since massive stars make a significant contribution to the metal enrichment of the inter-stellar medium (ISM), the proportion of massive stars and hence the IMF affects the mean metallicities of the model galaxies. In this study we use a Kennicut IMF (Kennicutt 1998), which was also used in the fiducial model of Hatton et al. (2003). Both the BH threshold and IMF increase the dynamical metal enrichment of the ISM. This changes not only the mean metallicity of the galaxies, and hence their absolute colour, but also makes the slope of the CMR steeper. This is because more massive galaxies, which have deeper potential wells, retain gas and therefore metals more effectively, leading to higher enrichment of the ISM and stellar populations that are born from it. However, less massive galaxies tend to lose their gas content anyway, so that a larger injection of metals into their ISM does not have a big impact on the metallicity of their stellar populations. As a result of this differential behaviour the slope of the CMR becomes steeper.

### 4 EVOLUTION OF THE CMR WITH REDSHIFT

We now check if it is possible to reconcile the model CMR with observational data at various redshifts. Figure 6 shows the predicted evolution of the model CMR from present day...
Table 2. Variations in CMR characteristics with baseline metallicity, threshold BH mass and IMF. The values in bold indicate the parameters used for this study. †BHT = Black Hole Threshold mass.

| Baseline metallicity = 0 | BHT = 45$M_\odot$ | BHT = 60$M_\odot$ | BHT = 120$M_\odot$ |
|-------------------------|------------------|------------------|------------------|
| Kennicutt IMF           | $-0.037 \pm 0.007$ | $-0.049 \pm 0.007$ | $-0.050 \pm 0.009$ |
|                         | 0.072             | 0.079             | 0.094             |
| Scalo IMF               | $-0.034 \pm 0.006$ | $-0.033 \pm 0.009$ | $-0.047 \pm 0.010$ |
|                         | 0.057             | 0.070             | 0.10              |

| Baseline metallicity = 0.1$Z_\odot$ | BHT† = 45$M_\odot$ | BHT = 60$M_\odot$ | BHT = 120$M_\odot$ |
|--------------------------------------|------------------|------------------|------------------|
| Kennicutt IMF                        | $-0.036 \pm 0.009$ | $-0.047 \pm 0.010$ | $-0.052 \pm 0.010$ |
|                                      | 0.075             | 0.082             | 0.12             |
| Scalo IMF                            | $-0.032 \pm 0.007$ | $-0.034 \pm 0.010$ | $-0.045 \pm 0.010$ |
|                                      | 0.061             | 0.078             | 0.10             |

to a redshift of 1.27, which is roughly the redshift limit of current observational evidence on early-type cluster galaxies (van Dokkum & Franx 2001). As before, the dotted line displays a linear least-squares fit and we also show a progressive one-sigma fit to the sample, with the error bars indicating the local spread of points about the best-fit relation. Figure 4 traces the evolution of the slope and the scatter. The shaded region denotes the area enclosed by the predicted slopes and their associated errors.

We note that the definition of a cluster elliptical will change with increasing redshift. We assumed in our analysis of present-day cluster ellipticals that DM halos with a mass equal to or greater than $10^{14}M_\odot$ host regions of highest baryonic density and therefore galaxy clusters. However, since DM haloes are being steadily formed through time, maintaining a hard mass cut-off of $10^{14}M_\odot$ for all redshifts would not be correct. To make this definition consistent with changing redshift we take into account the accretion history of DM halos in the model. We first compute an average accretion history of the present-day DM haloes with masses of $10^{14}M_\odot$ and above as a function of redshift. At each redshift we then define a cluster hosting DM halo as one whose mass is equal to or exceeds the value given by the average accretion history. We note that our values are consistent with van den Bosch (2002) who provides theoretical prescriptions for computing universal DM mass accretion histories.

We see from Figure 7 that there is gradual evolution in the CMR slope, although in the range $0 < z < 0.8$ the evolution in the slope is zero within the errors. However, once we move out to $z = 1.23$ the change in slope is appreciable compared to the value at present day. Within the errors, we see that at high redshifts (e.g. $z = 1.23$) the CMR loses any detectable slope, partly because the expected increase in the scatter masks any correlation that may be present.

In Figure 7 we put the evolution of the predicted CMR in the context of observational evidence. We intentionally use a variety of sources across various passbands. As men-
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Figure 7. Redshift evolution of the slope and scatter in the model (U-V) vs. V CMR. Although the evolution in the slope is zero within the errors in the range $0 < z < 0.8$, the change in the slope from the value at present day becomes appreciable at $z = 1.23$.

Figure 8. CMR evolution with redshift: model vs. observations. Filled circles represent model values and open circles represent observational results. The observational data from left to right are taken from: Bower et al. (1992) (marked), Scodeggio (2001) (marked), van Dokkum et al. (1998), Ellis et al. (1997), van Dokkum et al. (2000), van Dokkum et al. (2001).

5 PROGENITOR BIAS

When comparing the slope and scatter of the CMR at various redshifts, we should ideally sample the *same stellar mass at every redshift*. Only then are the slope and scatter truly meaningful tracers of the star formation history of the daughter mass seen today. However, an unavoidable result of the merger paradigm is that since early-type systems form through the amalgamation of late-type units, a progressively larger fraction of the stellar mass we see today in cluster ellipticals is locked up in late-type (spiral and irregular) units at higher redshifts. Hence the early-type systems at high redshift form a progressively narrower subset of the progenitors of present-day elliptical systems. Consequently, by not taking into account these late-type progenitors we introduce a bias in the CMR, mainly in terms of the observed scatter. In this section we quantify the effect of this progenitor bias.

Although tracing an astronomical object back through time is impossible observationally, it becomes a simple exercise within the model.

In Figure 9 we restrict ourselves to the progenitor set of present-day cluster ellipticals. We show only those galaxies (regardless of morphology) that eventually contribute to the formation of cluster ellipticals which exist at $z=0$. We are therefore tracing the *same stellar mass* back through time, regardless of the type of system that hosts it. Figure 10 indicates how much of the progenitor set of present-day cluster ellipticals is composed of fully-formed ellipticals at any given redshift. It becomes clear from Figure 10 that if we look solely at the elliptical progenitors of present-day cluster ellipticals we sample a progressively thinner fraction of the progenitor set at higher redshift. Although restricting ourselves to this subset of progenitors seems to give a CMR which maintains its slope and scatter with redshift (Figure 6), an *elliptical-only* CMR can only be used to constrain the SFH of the part of the stellar mass in present-day cluster ellipticals that is contained *solely* in early-type systems at any given redshift. However, since the subset of elliptical progenitors is *not representative of all the stellar material at present day*, we cannot use the evolution of an elliptical-
Figure 9. Progenitor bias: filled circles are ellipticals, triangles are S0s and open squares are late-type systems (spirals and irregulars). All galaxies are progenitors of the galaxies at $z = 0$. The shaded region indicates the mean elliptical-only relation and its associated errors taken from Figure 6.

Figure 10. The number of fully formed elliptical progenitors of present-day cluster ellipticals at a given redshift. The remaining mass is hosted by late-type systems.

only CMR to constrain the SFH of the entire stellar mass of present-day cluster ellipticals.

We find that including the late-type progenitors of early-type systems causes the scatter to increase at least three or four fold in the range $z > 0.8$, compared to the elliptical-only scenario.

Figures 9 and 10 show that the merger paradigm does indeed expect to have fully formed elliptical galaxies evolving passively at redshifts where CMR observations have been conducted. However, the elliptical-only CMR at high redshift does not correspond to the elliptical-only CMR at present day and comparisons between the two give a heavily biased picture of the star formation history of elliptical galaxies and has serious implications for the ability of the CMR to discriminate between the monolithic collapse and hierarchical merger paradigms. We discuss this point in the next section.

6 THE CMR AS A DISCRIMINANT BETWEEN FORMATION PARADIGMS

The issue of progenitor bias lies at the heart of the effectiveness of the CMR in discriminating between early-type formation models. If we believe that early-type systems are solely products of monolithic collapse at high redshifts, e.g. $z \geq 2$, then the progenitors of present day ellipticals in the redshift range $0 < z < 1.27$ must necessarily be ellipticals, since these systems were already in place much earlier at $z \sim 2$. Hence we do not need to worry about late-type systems in determining the CMR because they play no part in the early-type formation process. The redshift evolution of the slope and the scatter would then be expected to be negligible in the range $0 < z < 1.27$. Indeed, early-type systems form a remarkably well-behaved set of objects in both paradigms.

A belief in the merger picture implies that some of the stellar mass which is found in ellipticals at present day is also present in bona fide ellipticals at high redshift. However, a progressively higher fraction of that stellar mass is contained in late-type systems at higher redshifts, so that looking only at the elliptical part of the progenitor set of present-day cluster ellipticals is no longer sufficient. In essence, the quantity (in this case the elliptical-only CMR) that is being used to discriminate between the two formation models is no longer model independent and therefore loses its usefulness as a discriminant. Unfortunately, if we do include late-type progenitors, the significant increase in scatter destroys any correlation that may exist between colour and luminosity, so that talking about a colour-magnitude relation may no longer be meaningful.

7 SUMMARY AND CONCLUSIONS

We have used a semi-analytical hierarchical galaxy formation model to investigate the existence and evolution of the CMR of elliptical galaxies in cluster environments. Our analysis shows that by constructing a CMR purely out of early-type systems, the predicted relation agrees well with observations at all redshifts in the range $0 < z < 1.27$. 


We have focussed on certain key issues that have perhaps enjoyed less attention in previous CMR studies. Firstly, we have highlighted sections of the literature which show that the traditional use of deriving galaxy colours within fixed apertures gives a distorted view of the CMR due to the presence of colour gradients in galaxies. Fixed aperture observations make the CMR steeper and tighter than it really is. Removing this fixed aperture effect produces a CMR that agrees well with the expectations of the merger paradigm. Nevertheless, it is worth noting that the CMR derived from the central regions of galaxies maintains a tight scatter and constant slope with redshift, which may suggest a high degree of co-evoluty in the formation processes of star populations in galactic cores. Secondly, we have argued that progenitor bias is a serious issue when using the redshift evolution of the CMR to discriminate between the monolithic and merger paradigms. In particular, in the merger paradigm, ignoring late-type progenitors is not possible since a progressively larger amount of stellar mass found in present-day cluster ellipticals is locked up in late-type star forming units at high redshifts. As a result, sampling only the elliptical part of the progenitor set to derive the star formation history is not meaningful. Thirdly, we have suggested that the elliptical-only CMR is not a useful discriminant between the monolithic and merger formation scenarios since it is significantly biased towards the monolithic picture. Although the merger paradigm satisfies the elliptical-only CMR in any case, restricting our studies to early-type systems does not provide meaningful information about the true star formation history of all the stellar mass that is found today in cluster ellipticals. However, the inclusion of late-type progenitors in CMR studies requires a belief in the merger paradigm in the first place. Hence what type of CMR we use depends upon our choice of formation paradigm and thus the CMR itself loses its ability to truly discriminate between formation scenarios.

The debate regarding these two competing theories of elliptical galaxy formation still remains an open one. Although there is clear evidence of interactions, mergers and recent star formation in early-type systems, a possible caveat is the inability of the merger paradigm to satisfy the high [Mg/Fe] ratios observed in luminous ellipticals (e.g. Trager et al. 2000a). These super-solar abundance ratios indicate a lack of enrichment from type Ia supernovae thereby constraining the duration of star formation and gas infall to timescales shorter than about 1 Gyr (e.g. Matteucci & Recchi 2001; Ferreras & Silk 2002). While the CMR has been used as an indirect tool for constraining the star formation history of cluster ellipticals, more direct sources of evidence might be required. If the BLE92 assertions are correct and the stellar mass in cluster ellipticals did indeed form at \( z > 2 \) then we should not find any traces of star formation after this epoch, which in a ΛCDM universe corresponds to an age of approximately 10 Gyrs. The merger models do of course predict star formation right up to the present day and one could assume that at least a small fraction of the resultant stellar mass could be locked up in globular clusters, which are the faintest stellar aggregations that can be accessed observationally.

Figure 11 shows the bulk distribution of stellar mass contained in cluster ellipticals. Overplotted globular cluster data from left to right: Larsen et al. (2003), Strader et al. (2003), Goudfrooij et al. (2001), Kissler-Patig et al. (2002), Yi et al. (2003). The key indicates the mass fractions corresponding to the colours used in the plot.

To conclude, we suggest that it seems increasingly likely that the monolithic collapse picture may simply be a subset of the merger paradigm and that the dominant mechanism for the formation of elliptical galaxies is through the merging of late-type progenitors.

ACKNOWLEDGEMENTS

We warmly thank Jeremy Blaizot, Roger Davies, Joseph Silk and Sadegh Khochfar for their careful reading of this manuscript and many useful discussions. We also thank Seok-Jin Yoon for constructive remarks related to this work. SK acknowledges PPARC grant PPA/S/S/2002/03532. This research has been supported by PPARC Theoretical Cosmology Grant PPA/G/O/2001/00016 (S. K. Yi) and has made use of Starlink computing facilities at the University of Oxford.

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