Secondary episodes of star formation in elliptical galaxies

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\begin{abstract}
We put upper limits on the secondary burst of star formation in elliptical galaxies of the González sample, based on the colour dispersion around the $U - V$ versus central velocity dispersion relation, and the equivalent width of H\textbeta absorption. Note that most of these galaxies locate in small groups. There is a significant number of H\textbeta strong galaxies that have $\text{EW}(\text{H}\beta) > 2$ Å, but they do not always have bluer colours in $U - V$. To be consistent with the small colour dispersion of $U - V$, the mass fraction of the secondary burst to the total mass should be less than 10 per cent at the maximum within the most recent 2 Gyr. This result suggests that even if recent galaxy merging has produced some ellipticals, it should not have been accompanied by an intensive starburst, and hence it could not involve large gas-rich systems. The capture of a dwarf galaxy is more likely to explain the dynamical disturbances observed in some elliptical galaxies.

The above analysis, based on the $U - V$, is not compatible with the one based on the line indices, which requires that more than 10 per cent of mass is present in a 2-Gyr-old starburst to cover the full range of the observed H\textbeta (de Jong & Davies). The discrepancy might be partly explained by the internal extinction localized at the region where young stars form. However, considering that the H\textbeta index might have great uncertainties both in models and in observational data, we basically rely on $U - V$ analysis.

\textbf{Key words:} stars: formation – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: stellar content.
\end{abstract}

\section{1 INTRODUCTION}
Elliptical galaxies in clusters are old. Dispersions of colours around the colour--magnitude (C--M) relation of cluster ellipticals are small at low and intermediate redshifts (Bower, Lucey & Ellis 1992b; Ellis et al. 1997). This strongly suggests that almost all stars in ellipticals formed at a high redshift, at least $z_f > 2$–3. The colour change of ‘red-envelope’ galaxies in high redshift clusters suggests that these galaxies formed at $z_f > 2$ and have evolved passively since then (Aragón-Salamanca et al. 1993). A similar implication is given by Mg\textbeta indices of ellipticals in clusters at intermediate redshift (Bender, Ziegler & Bruzual 1996). Recent analyses of the C--M relations of cluster E/S0s at high redshift, all of which are morphologically classified by \textit{Hubble Space Telescope (HST)} imaging, also require that ellipticals should form at $z_f > 2$ (Kodama 1997; Stanford, Eisenhardt & Dickinson 1998). An implication derived from this observational evidence is in full agreement with the picture predicted by a galactic wind model for the formation of elliptical galaxies (Larson 1974; Arimoto & Yoshii 1987; Kodama & Arimoto 1997): elliptical galaxies should form by the dissipative collapse of a protogalactic massive cloud, during which stars would be born intensively. The star formation ceased when the gas in the galaxy was expelled by the supernovae-driven galactic wind. Galaxies then evolved passively without experiencing any further significant episodes of star formation.

Nevertheless, there is a growing body of evidence indicating that elliptical galaxies, in particular in the low-density environment, might have experienced secondary formation of stars in the recent past (e.g., Schweizer et al. 1990; Schweizer & Seitzer 1992; Rose et al. 1994; Bressan, Chiosi & Tantalo 1996; Barger et al. 1996). Schweizer & Seitzer (1992) analysed colours and line indices of E/S0 galaxies in the field as well as in groups, and found that $U - B$ and $B - V$ become systematically bluer and H\textbeta indices become stronger as the amount of fine structure increases, which suggests that the secondary episode of star formation is related to dynamical disturbances of galaxies, probably caused by mergers and/or interactions with other galaxies (see also Schweizer et al. 1990). Hierarchical clustering models of galaxy formation based on the CDM hypothesis (Kauffmann, White & Guiderdoni 1993; Cole et al. 1994) suggest that the star formation took place recently in elliptical galaxies due to galaxy merging. The CDM-based models...
predict a significant fraction of starburst at $z_f < 1$ in elliptical galaxies especially in the field.

With a help of the population synthesis model proposed by Worthey (1994), de Jong & Davies (1997) have recently analysed the H$\beta$ and [MgFe] indices of elliptical galaxies, spectra of which were taken by González (1993). Most of the galaxies are members of small groups. They estimate the amount of starburst that is required to reproduce the H$\beta$ and disc-to-total light ratio (D/T). The resulting fraction of young stars is larger than 10 per cent if they are 2 Gyr old.

Barger et al. (1996) demonstrate that at least 30 per cent of cluster galaxies in AC 103, 114, and 118 ($z = 0.31$) seem to have undergone a secondary burst of star formation during the last $\sim 2$ Gyr prior to the epoch of observation, though many of them are regular E/S0s. This implies that the frequency of secondary burst is very high even for cluster ellipticals, where the galaxy–galaxy merger is supposed to be less frequent than in the field.

Independently, broad-band colours can put much stronger constraints on the nature of secondary starbursts in cluster E/S0s. Bower et al. (1992b) analysed $U - V$ colour dispersions around the C–M relations of the Coma and Virgo clusters, and found that the amount of mass involved in the secondary starburst should be less than 10 per cent if the age of the starburst population is 5 Gyr. If a younger age of 2 Gyr is assumed, the starburst population should be quite small, no more than a few per cent.

The problem arising here is an apparent inconsistency between the two types of analyses, the line indices versus the colour dispersion. The lines always indicate a larger fraction of the secondary burst population. Recent studies tend to heavily rely on the line indices data to derive the contribution of the secondary burst population (e.g. Worthey 1994; de Jong & Davies 1997). However, the burst strength thus derived should also explain the observed $U - V$, since at least the synthesized broad-band colours are much more reliable than the line indices, which are usually calculated independently of colours by using empirical polynomial fitting functions (e.g. Worthey 1994; Vazdekis et al. 1996). In this paper, therefore, we analyse $U - V$ and H$\beta$ indices of ellipticals in the González (1993) sample, and derive new constraints on the amount of young population.

In Section 2 we compile the data used in this study. In Section 3 we describe the method used to compute models for elliptical galaxies with a secondary starburst. The resulting constraints for the star formation history in ellipticals are given in Section 4. In Section 5, we discuss possible causes for the discrepancy between $U - V$ and H$\beta$ analysis, and conclude this paper.

2 DATA

2.1 Source

We have analysed a whole sample of 41 elliptical galaxies, for which González (1993) gives measurements of the conspicuous Lick line strengths, H$\beta$ line strengths (at $\lambda \sim 4860$ Å) and central velocity dispersions $\sigma_e$ (within the inner 5 arcsec) are taken from González (1993), and broad-band colours are taken from RC3 (de Vaucouleurs et al. 1991). Following Schweizer & Seitzer (1992), we define $(U - V)_{b,0}$ as

$$(U - V)_{b,0} = (U - V)_b + [(U - V)_{T,0} - (U - V)_T],$$

where subscript $T$ refers to global colours, subscript 0 indicates colours corrected for the extinction due to interstellar dust in our Galaxy as well as for the redshift, and subscript $e$ refers to average colours within an effective radius. Internal extinction is neglected because no values are given in RC3, but an argument is given later on the possible influence of the internal extinction (see Section 5, below). Observational errors are taken into account in $(U - V)_b$, but errors involved in the correction procedure in deriving $(U - V)_{b,0}$ are not included because they are not given in RC3. Therefore the errors of $(U - V)_{b,0}$ could be substantially larger than those given in Figs 2, 4, 6, and 7 (see below). This would not affect our arguments significantly, however, since our main concern is to understand why the dispersion in colours is so small along the $(U - V)_{b,0}$ versus log $\sigma_e$ relation (see Fig. 2, below) while some galaxies are showing strong evidence of young stars in the measured H$\beta$ lines. Errors in the velocity dispersion are very small ($\sim 1$ per cent; González 1993), and are therefore ignored.

2.2 H$\beta$ strong galaxy

The 10 galaxies among González’s sample show strong H$\beta$ absorption, which may be a result of contamination from some young stars in these galaxies. By analogy with the H$\beta$ strong galaxies defined by Couch & Sharples (1987), we define H$\beta$ strong galaxies as those having an equivalent width EW(H$\beta$) larger than 2 Å. González (1993) gives H$\beta$ indices for three different apertures: nuclear 5 arcsec, $r_c/8$, and $r_c/2$, where $r_c$ is the effective radius of elliptical galaxies. We adopt the $r_c/2$ aperture for H$\beta$ indices, since it is the closest to $r_e$ within which the colours in RC3 are defined. This would minimize the effect of the H$\beta$ line strength gradient which is sometimes shown for elliptical galaxies (Gorgas, Efstathiou & Aragón-Salamanca 1990; Davies, Sadler & Peletier 1993; González 1993). Fig. 1 shows the H$\beta$ index versus central velocity dispersion (log $\sigma_e$) for the whole of González’s sample. The filled circles represent the H$\beta$ strong galaxies. The NGC number is attached to each of them. The solid line corresponds to a sequence of model ellipticals (see Section 3). Note that the H$\beta$ strong galaxies are more than 0.3 Å away from the sequence.

![Figure 1. The H$\beta$ versus log $\sigma_e$ diagram for 41 elliptical galaxies. Data are taken from González (1993). The filled circles show the H$\beta$ strong galaxies to which the NGC number is attached. The solid line shows a sequence of galactic wind models (metallicity sequence) for elliptical galaxies calculated by Kodama & Arimoto (1997).](https://academic.oup.com/mnras/article-abstract/300/1/193/1130549)
they are expected to be appreciably bluer if suffering from the secondary burst of star formation recently. Five galaxies out of 10 Hβ strong galaxies – NGC 507, NGC 584, NGC 1700, NGC 3377, and NGC 7454 – locate below (bluer) the line of the C–σ relation in Fig. 2. These galaxies are likely to have a considerable number of young stars. However, aside from NGC 3377, these galaxies are no bluer than 0.1 mag, which indicates little contamination by young stars of the galactic light. The Hβ strong galaxies should contain a certain number of young stars, and yet some of them do not show any evidence in colours of young stars. In Section 3, we build a series of models for elliptical galaxies with the young population superposed on to the underlying old populations, and examine how many young stars can be in hiding to give compatible Hβ line strengths while keeping the C–σ relation tight.

3 MODEL

3.1 Elliptical galaxy models

We build models for elliptical galaxies that have experienced the secondary burst of star formation by superposing the young stellar population on to the old underlying populations. For the underlying populations, we adopt the metallicity sequence models of elliptical galaxies calculated by Kodama & Arimoto (1997) and Kodama (1997). These models are calibrated to reproduce the C–M relation of elliptical galaxies in the Coma cluster by changing a galactic wind epoch as a function of initial mass of a galaxy. This is equivalent to changing the mean stellar metallicity of galaxies along the C–M relation. The age of the galaxies is assumed to be 12 Gyr. All stars formed very quickly before the wind (<0.5 Gyr). The time-scale of star formation is assumed to be 0.1 Gyr. A Salpeter-like initial mass function (IMF) is assumed with a slope $x = 1.10$ (the Salpeter IMF corresponds to $x = 1.35$ in our definition). The lower and the upper mass cut-offs $m_1$ and $m_2$ are set to be 0.1 and 60 M$_\odot$, respectively. The mean stellar metallicity ($\log Z/Z_\odot$) decreases from 0.0 to −0.5 for the range of 6 mag covered by the C–M relation ($M_V = -23.0$ to −17.0 mag). Chemical evolution is taken into account under the so-called infall model scheme (cf. Köppen & Arimoto 1990). The models are shown to match very well with the observed C–M relations of elliptical galaxies in distant clusters (Kodama & Arimoto 1997; Kodama et al. 1998).

The velocity dispersion is assigned to each model galaxy with a help of the $(U-V)_{b,0}$ versus log $\sigma_0$ relation defined in Section 2.3 (solid line in Fig. 2) as:

$$\log \sigma_0 = 2.024[(U-V)_{b,0} - 0.339].$$

(2)

where we use a theoretical $U-V$ for $(U-V)_{b,0}$. The Lick spectral indices are calculated by using the polynomial analytical fits given by Worthey, Faber & González (1992). The synthesized Hβ indices of the underlying galaxy models with various initial masses are shown in Fig. 1 by the solid line.

3.2 Secondary starburst models

We assume that the secondary burst happened instantaneously. In such a case, the spectrum of the burst population is approximated by the so-called simple stellar population (SSP) model (cf. Buzzoni 1989). Thus we ignore the metal enrichment during the secondary burst. The IMF slope of the secondary population is assumed to be $x = 1.35$ (the Salpeter IMF). $m_1$ and $m_2$ are the same as those of the underlying population. Note we adopt a different IMF slope for the burst population from that of the underlying population, simply

Figure 2. The $(U-V)_{b,0}$ versus log $\sigma_0$ diagram for E/S0 galaxies. Hβ strong galaxies are shown by the filled circles to which the NGC number is attached. The solid line gives the regression line for the data, and the coefficients are indicated on the head of the figure as is the standard deviation of colours. The regression line for Coma and Virgo ellipticals observed by Bower et al. (1992b) is also shown by the dot-dashed line.
because there is no reliable estimate available. However, our conclusion would not be affected by this choice of IMF slope. If we were to use $x = 1.10$ for the burst population instead, the acceptable burst strength would become even smaller as a result of more numerous young stars. Therefore, our conclusion would be strengthened.

The evolution of $U - V$ and Hβ index of the SSP models are illustrated in Fig. 3. The thick dashed lines and the thick solid ones represent the SSP models with $Z = 0.008$ and 0.02, respectively. The thin lines represent various SSP models with the solar abundance ($Z = 0.02$) available in the literature (Worthey 1994; Bressan et al. 1996; Vazdekis et al. 1996). The age of the burst population $T_b$ is varied from 0.1 to 5 Gyr as a free parameter. If the secondary burst is induced by capturing a small gas-rich galaxy, as is most likely, the mean stellar metallicity of the burst population should not exceed the solar metallicity, since typical metallicities of dwarf irregulars are well below the solar value (Skillman, Kennicutt & Hodge 1989).

Even if the chemical enhancement during the burst is considered, the average metallicity of the burst population hardly exceeds the solar value unless the IMF slope is significantly flatter than the Salpeter IMF. Therefore we adopt $Z_b = 0.008$ and $Z_b = 0.02$ as the representative metallicities of the secondary burst. The burst strength ($f_b$) is defined by a mass fraction of burst population to the whole galaxy at the present epoch (12 Gyr), and is allowed to vary from 0.1 to 20 per cent. We assume that the velocity dispersion does not change before or after the burst, since the mass involved in the secondary burst is usually small compared to that of the underlying population. Even if the fraction of the burst is as high as 20 per cent in mass, the resulting increase of the velocity dispersion is at most $\Delta \log \sigma_0 = 0.05$ if the galaxy is in virial equilibrium before and after the burst. If the dark matter dominates the galaxy potential, the influence of the burst population to the velocity dispersion should be less significant.

**Figure 4.** Models in the $(U - V)_{b,0}$ versus log $\sigma_0$ diagram for elliptical galaxies with the secondary starburst. Circles show our sampled galaxies and the dotted line gives the regression line for galaxies shown in Fig. 2. The dashed line and the solid line indicate models with a secondary starburst of $Z_b = 0.008$ and 0.02, respectively. Burst age $T_b$ is assumed to be 2.0 Gyr. The burst strength $f_b$ is increased from 2 (top) to 20 per cent (bottom).

Along the C–σ relation, the young SSP model is superposed in such a way that the mass fraction of the young population to the total mass is equal to a given burst fraction $f_b$. The $U - V$ colour and Hβ index of a total galaxy are calculated from the resulting composite spectrum.

## 4 COMPARISON

Fig. 4 illustrates the colour change arising from an increase of the burst strength in the $(U - V)_{b,0}$ versus log $\sigma_0$ diagram. Burst age $T_b$ is fixed to be 2 Gyr. The open and filled circles show the same galaxies as in Fig. 2, and the dotted line gives the regression line for the data, along which we assign the underlying galaxies. The dashed line and the solid one correspond to the metallicity of the burst $Z_b = 0.008$ and 0.02, respectively. The burst strength, $f_b$, is increasing from the top to the bottom. Apart from one exception, NGC 3377, the maximum burst strength allowed to be consistent with the data is less than ~7 per cent for $T_b = 2$ Gyr. In the same way, models with various combination of $T_b$, $f_b$, and $Z_b$ are confronted with the data, and the upper limit of the burst strength is investigated for each case. The results are summarized in Table 1. The acceptable amount of colour change $\Delta(U - V)$ as a result of the young population is set to $-0.1$ at log $\sigma_0 = 2.35$. The maximum burst strength $f_b$ is adjusted in such a way that $\Delta(U - V)$ reaches this limit for a given set of $T_b$ and $Z_b$. As a result, we find that the permitted range of the burst strength should be very small; typically less than a few per cent in mass, at most 4–7 per cent within the most recent 2 Gyr.

The above number is considerably smaller than that given by de Jong & Davies (1997), who obtained a 10–15 per cent young population for $T_b = 2$ Gyr burst to reproduce the strong Hβ line strengths ($\geq 2$ Å). Independently, as described in Section 3, we calculated Hβ indices for the secondary starburst models to see the consistency. The results are shown in Fig. 5 for the case of
becomes too blue in \( U - V \). We will discuss this \( U - V \) versus H\( B \) discrepancy later.

If the age of the secondary burst is as low as 0.5–1 Gyr, as suggested from the numerical simulation of shells around dynamically disturbed ellipticals (Hernquist & Quinn 1987), the burst strength should be quite small, e.g. less than 1–2 per cent. Conversely, if we assume higher burst ages, the limit of \( f_b \) becomes larger (more than 20 per cent for \( T_b = 5 \) Gyr, for example), but the \( (U - V) - \text{H}\beta \) discrepancy becomes larger.

For reference, the \( U \)– and \( V \)-band luminosity-weighted mean age of stars in a galaxy \((T)_U, (T)_V\) are also given in Table 1. These are defined as:

\[
\log(T)_{U,V} = \frac{\sum \log(T) L_{U,V}}{\sum L_{U,V}},
\]

where summation is taken for all stars in a galaxy. Thus, the lower limit of \((T)_U\) is 7.3–9.1 Gyr and that of \((T)_V\) is 8.4–10.5 Gyr. These are much higher than the age of the bulk of ellipticals that Worthey, Trager & Faber (1996) assigned from the Balmer line indices. These authors find a significant number of extremely young elliptical galaxies with ages of only 2–3 Gyr. The mean age is also quite young, e.g. 4–5 Gyr, nearly half of what we find. The discrepancy in the results between the analysis based on the colours and the one based on the line indices can be seen clearly here.

In conclusion, apart from NGC 3377, which could be the only candidate that might actually have a burst strength of up to 15–20 per cent for \( T_b = 2 \) Gyr and could be consistent with its H\( B \) strength, the intensity of the secondary starburst should be only a few per cent in mass to be compatible with the observed \( U - V \). However, this is not strong enough to explain the H\( B \) strong galaxies.

**5 DISCUSSION AND CONCLUSIONS**

So far we have calibrated the models of the underlying old populations using the linear regression line of the data on the \( C-\sigma \) diagram, supported by the existence of the mass–metallicity relation for elliptical galaxies as discussed in Section 2.3. However, one could alternatively take the location of the underlying population as the reddest envelope of the sample galaxies, if all galaxies bluer than the red envelope are regarded as being contaminated by young stars. Although we believe this is unlikely (as discussed above), we estimate how much the upper limit of \( f_b \) could be increased if this effect is the case. If we take the red envelope at 0.07 mag redder than the regression line, the acceptable burst strength increases to \( f_b \sim 10 \) per cent. Therefore, even in this case, the maximum burst strength in mass fraction should be less than 10 per cent at most, within the most recent 2 Gyr.

Furthermore, one may claim that low-mass systems more often have discy shapes and can contain more young stellar populations (e.g. Kormendy & Bender 1996), therefore the slope of the \( C-\sigma \) relation of the underlying old population might possibly be flatter at the faint end than that defined in this paper. This is equivalent to weakening the metallicity variation as a function of galaxy mass and to introducing some age difference instead. In fact, as shown in Fig. 6 where the sample galaxies are plotted in the \( U - V \) versus H\( B \) diagram with the secondary burst models superposed, the four H\( B \) strong ellipticals with low dynamical masses (log \( \sigma_0 \) < 2.15) could be explained consistently both in \( U - V \) and H\( B \) at the same time with some combination of metallicity and burst strength, if one could neglect the \( C-\sigma \) relation. The other H\( B \) strong ellipticals with larger masses locate out of the model grid, and the \((U - V) - \text{H}\beta \) discrepancy is quite evident for these galaxies in any case. However, if lower mass systems tend to be more contaminated by young stars,
the slope of the C–α relation and hence the C–M relation is expected to vary from cluster to cluster, given that the colour is very sensitive to a small difference in the number of young stars. This trend is far from what we actually observe both locally and at high redshifts (Garilli et al. 1996; Stanford et al. 1998; Kodama et al. 1998; López-Cruz 1997). It has been shown that most clusters have a common slope when compared to the Coma or Virgo cluster. Even if it were the case that low-mass galaxies would contain more young stars, the \( (U - V) - H_\beta \) discrepancy could not be compensated for. In order to be consistent with the strong \( H_\beta \) indices of these low-mass galaxies, the secondary starburst of 15–20 per cent in mass is required with \( T_b = 2 \) Gyr. If they were to have such a strong starburst (15 per cent), the colour of the underlying population should be \( U - V = 1.5 \), just comparable to the typical colour of the rest of ellipticals, and we would no longer see the C–α relation for the underlying old population. The 15 per cent burst with \( T_b = 2 \) Gyr gives luminosity-weighted ages of \( (T)_U = 5.2 \) and \( (T)_V = 6.2 \), which are 6–7 Gyr younger than the bulk of more massive ellipticals (which corresponds to about 4 mag brighter using the Fabor–Jackson law). As expected, the 6–7 Gyr difference in the 4 mag range of the C–M relation is almost comparable to a pure age sequence discussed in Kodama & Arimoto (1997) and Kodama et al. (1998), which is absolutely rejected by the evolution of the C–M slope as a function of redshift. Therefore, the observed C–M relation of clusters does not support the idea that the low-mass \( H_\beta \) strong ellipticals have experienced much stronger secondary bursts than our estimate.

After all, the \( (U - V) - H_\beta \) discrepancy does remain; i.e., the integrated \( U - V \) colour of Gonzalez’s sample of ellipticals permits only 10 per cent of the secondary stellar population at most, while the strong \( H_\beta \) indices suggest much larger burst strengths. We here consider possible reasons for this discrepancy.

1. **Model uncertainty.** One possible reason is that the \( H_\beta \) synthesis model, based on the empirical calibration of Worthey et al. (1992), may still be premature partly because the scatter around the polynomial fitting lines might be too large and/or because the zero-point of the model might be uncertain. \( U - V \) could have uncertainties as well (Charlot, Worthey & Bressan 1996), but they are expected to be small, at ages 1–2 Gyr or less, since at such low ages, \( U - V \) colour is driven primarily by the evolution of the main-sequence turn-off stars, and is relatively simple to model.

2. **Emission correction.** González (1993) corrected the contamination of \( H_\beta \) emission for the equivalent width of \( H_\beta \) absorption by using the intensity of [O ii] emission. Although this empirical procedure is reasonable, it causes uncertainty in the \( H_\beta \) indices. If the correction tends to be overestimated, the real \( H_\beta \) absorption could be much lower and consistent with \( U - V \) analysis.

3. **Aperture effect.** \( H_\beta \) indices are defined in the \( r_e / 2 \) aperture, while the colours are defined in the \( r_e \) aperture. If all stars of the secondary population are formed locally within \( r_e / 2 \), the allowed burst strength could be 1.56 times larger within \( r_e / 2 \) following de Vaucouleurs (1948) \( r^{1/4} \) law. This could rise the model \( H_\beta \) indices by about 0.1–0.15 Å, and it could (marginally) make up the discrepancy. According to Davies et al. (1993), however, \( H_\beta \) absorption is constant or increasing with radius in almost all cases of elliptical galaxies in their sample. Though this could be partly a result of the dilution of the \( H_\beta \) absorption feature by emission in the centres of galaxies (Davies et al. 1993), \( H_\beta \) would be hardly changed between the \( r_e / 2 \) and \( r_e \) apertures.

4. **Internal dust extinction.** The internal dust extinction is expected to have more effect on \( U - V \) colour than on \( H_\beta \) indices. It would redden the \( U - V \) of galaxies without reducing \( H_\beta \) indices much, and could dissolve the discrepancy. To see the effect in more detail, the internal extinction is taken into account in the model spectra in a simple way. The extinction law is taken from Mathis (1990). We assumed that the dust distribution in the galaxies is localized only in the region where the secondary burst had occurred. Hence we applied the extinction correction only for the burst population, and not for the old underlying population. In Figs 7
and 8, the effect of extinction is shown for $U - V$ and H$\beta$, respectively. $A_V$ is changed as 0.0, 0.5, and 1.0 mag. The model with $f_b = 20$ per cent and $A_V = 0.5$ mag, for example, could possibly reproduce some of the H$\beta$ strong galaxies both in $U - V$ and H$\beta$. The effect of internal extinction certainly allows a higher upper limit to the burst strength. A study of the infrared colours of the González sample would help, since the SED at longer wavelengths is less vulnerable to dust extinction.

In summary, although considerable dust extinction for the burst population could solve the discrepancy between $U - V$ and H$\beta$ analyses, we rely on $U - V$ at the moment, considering that the H$\beta$ might have great uncertainties both in models and in observational data. In this case, we can put a strong constraint on the secondary episode of star formation in ellipticals: elliptical galaxies, regardless of their environments, experience little secondary star formation in the recent past. For example, the mass fraction of the young burst population should be quite small, typically less than 4–7 per cent, and 10 per cent at most within the most recent 2 Gyr. This suggests that the dynamical disturbance found in some ellipticals is more likely to be caused by the capture of a dwarf galaxy with a mass of order $10^9$–$10^{10}$ M$_\odot$, rather than by a merging of two galaxies of comparable size. If ellipticals are formed by the recent mergers of comparable galaxies, as hierarchical clustering models of the Universe suggest, this should have proceeded without any significant star formation. However, it is yet to be studied in detail how such a process could create the observed C–M relation of ellipticals.

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