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Modelling the colour evolution of luminous red galaxies – improvements with empirical stellar spectra

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ABSTRACT

Predicting the colours of luminous red galaxies (LRGs) in the Sloan Digital Sky Survey has been a long-standing problem. The g, r, i colours of LRGs are inconsistent with stellar population models over the redshift range $0.1 < z < 0.7$. We provide a solution to this problem, through a combination of new astrophysics and a fundamental change to the stellar population modelling. We find that the use of the empirical library of Pickles, in place of theoretical libraries based on model atmosphere calculations, modifies the evolutionary population synthesis predicted colours exactly in the way suggested by the data. The reason is a lower (normalized) flux in the empirical libraries, with respect to the theoretical ones, in the wavelength range 5500–6500 Å. The effect increases with decreasing effective temperature roughly independently of gravity. We also find that other recent libraries such as MILES and STELIB behave the same way. We further verified that [α/Fe] effects on stellar spectra cannot substitute the effect of the empirical library because they make both colours bluer. The astrophysical part of our solution regards the composition of the stellar populations of these massive LRGs. We find that on top of the previous effect one needs to consider a model in which ∼3 per cent of the stellar mass is in old metal-poor stars. Other solutions such as an overall slightly subsolar metallicity or young stellar populations can be ruled out by the data. The percentage of the metal-poor subpopulation may be affected by the consideration of abundance-ratio effects though in the framework of present calculations the metal-poor option is favoured. Our new model provides a better fit to the colours of LRGs and gives new insight into the formation histories of these most massive galaxies. The new model will also improve the k- and evolutionary corrections for LRGs which are critical for fully exploiting present and future galaxy surveys.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: stellar content – cosmology: observations.

1 INTRODUCTION

Age dating the stellar populations of galaxies provides us with a cosmic time-scale which is independent of cosmological models and allows the use of galaxies as cosmological probes (e.g. Jimenez & Loeb 2002). The interpretation of galaxy spectra in terms of stellar populations is also the only effective way of reconstructing their star formation histories, which allows one to get clues on the still poorly known process of galaxy formation. There is a long history of research in this area. We provide here a selection of recent works (Kauffmann et al. 2003; Nelan et al. 2005; Thomas et al. 2005; Bernardi et al. 2006; Jimenez et al. 2007; Panter et al. 2007) and refer the reader to Renzini (2006) for a comprehensive review of studies at both low and high redshift.

Studies of galaxy evolution based on the Sloan Digital Sky Survey (SDSS) data of luminous (massive) red galaxies (LRGs) have highlighted a potentially fundamental problem with the rest-frame optical of stellar population models. As first noted by Eisenstein et al. (2001), single-burst models with single solar metallicity are systematically too red in the $g - r$ observed frame in the redshift range 0.1 to 0.4 (see Fig. 1, left-hand panel). This discrepancy could not be cured by adopting more complex stellar population models with various star formation histories or different (single) metallicities or different stellar population model codes. To be able to analyse the data, Eisenstein et al. (2001) applied a shift of 0.08 mag to the models.

Wake et al. (2006, hereafter W06) extended this study by including the $r - i$ colour as a further constraint and by adding the

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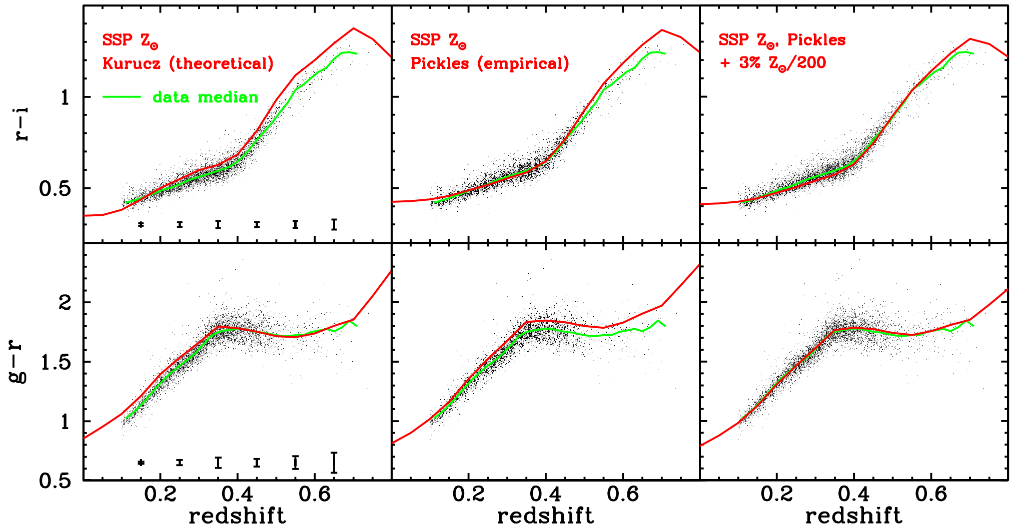

Figure 1. The $g - r$ and $r - i$ colours of LRGs as functions of redshift (points; data from W06). The median is given by the green line. Typical errors as function of redshift indicated by the error bars. Left-hand panels: a solar-metallicity passively evolving, single-burst model with an age of 12 Gyr at redshift zero (red line). Middle panels: same data as in the left-hand panel. The stellar population model uses the Pickles (1998) empirical spectral library instead of the theoretical one (see the text). Right-hand panels: same data as in the left-hand panel with a composite model with 3 per cent by mass of metal-poor [Z/H] = −2.2 stars. Both the metal-rich and the metal-poor component are 12 Gyr old at redshift zero. The metal-rich component uses the Pickles (1998) empirical spectral library.

2dF SDSS LRG and Quasar (2SLAQ) survey sample (Cannon et al. 2006) to increase the redshift range to $z \sim 0.8$, demonstrating further discrepancies between the models and data. While the models are too red in the observed frame $g - r$ at low redshift, the $r - i$ colour turns out to be too blue (see Fig. 1, left-hand panel). This pattern changes with increasing redshift such that the predicted $r - i$ colour becomes too red, while the predicted $g - r$ matches the data (all observed frame). Fig. 1 in W06 demonstrates that the addition of star formation does not solve the problem. Indeed, the light of young, blue stars while curing the $g - r$ syndrome at the lowest redshifts worsens the discrepancy in the $r - i$ colour at low redshifts and the $g - r$ colour at high redshifts, such that colours in the model become too blue. The origin of this mismatch has remained a puzzle so far, and has serious consequences for the interpretation of current observations and the planning of future galaxy surveys. Here, we provide a solution to this problem and present a working stellar population model.

The Letter is arranged as follows. In Section 2, we recall the features of the LRG sample. In Section 3, we present the working solution and comment on other options. Conclusions are given in Section 4.

2 THE DATA SAMPLE

W06 extract their sample of LRGs from the SDSS multicolour photometry (SDSS; York et al. 2000). Spectroscopic redshifts are taken from the SDSS in the redshift range $0.15 < z < 0.37$, and from the 2SLAQ survey (Cannon et al. 2006) in the redshift range $0.45 < z < 0.8$. At $z > 0.4$, we use the deeper multi-epoch data in Stripe 82. LRGs from both surveys were selected in a consistent way using the same rest-frame colour cuts, under the assumption that they were old, passively evolving galaxies, in order to make sure that the same galaxy population is sampled at all redshifts (see W06 for details).

Obviously, the sample definition depends on the colour selection, which, in turn, depends on the model adopted to identify the LRGs. This is what we should call model-dependent data setting. One of the worst consequences of the discrepancy between data and models is that in order to minimize the effect of incorrectly k-correcting the data a conspicuous part of the initial data base had to be discarded. This fraction was as substantial as 85 per cent in W06. Hence, besides the general astrophysical goal of understanding the stellar populations of luminous, massive galaxies, there is the more practical need to optimally exploit the precious data emerging from present and future surveys of LRGs to high redshift. To ensure self-consistency, the data used in this Letter have been reselected using the Maraston (2005, hereafter M05) models.

In the following, we assume that galaxies start forming stars at a redshift of five, as suggested by the local fossils (e.g. Kauffmann et al. 2003; Nelan et al. 2005; Thomas et al. 2005; Bernardi et al. 2006; Jimenez et al. 2007), which fixes their present age to be about 12 Gyr.

3 THE WORKING MODEL

The problem as explained in Section 1 is illustrated in the left-hand panel of Fig. 1, which is a remake of fig. 1 by W06. The red line refers to a single-burst model (simple stellar population, SSP) with a solar metallicity and an age of 12 Gyr at redshift zero. Residuals are shown in Fig. 2. The right-hand panels of Figs 1 and 2 show the solution to the problem using our new model. The latter is based on two modifications: the replacement of theoretical stellar atmospheres by empirical ones and the inclusion of a small (3 per cent by mass), metal-poor subcomponent. Details of this model are described in the following sections.

3.1 Inclusion of empirical stellar atmospheres

The simultaneous mismatch in opposite directions of colours sampling close rest-frame wavelengths was suggestive to us of a shortcoming in the model stellar spectra (e.g. Lejeune, Cuisinier & Buser 1997, BaSeL, based on the Kurucz 1979 library) that are commonly used in most population synthesis models. To explore this path, we consider empirical spectral libraries as a substitute to the theoretical

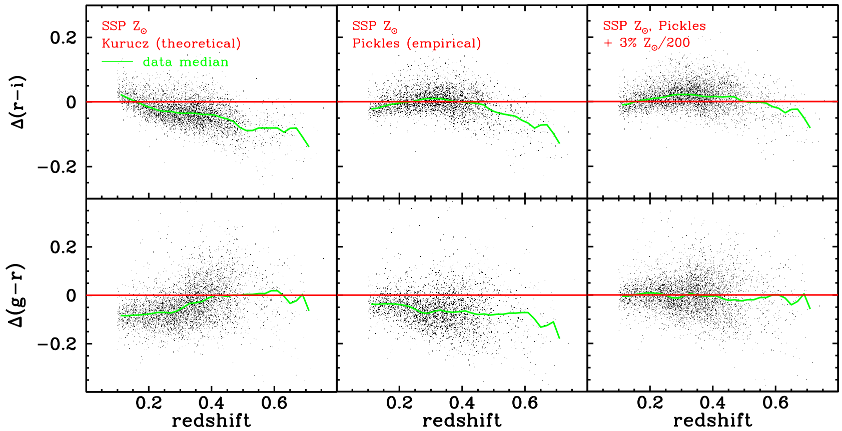

Figure 2. Residuals of the plots shown in Fig. 1.

ones and compute stellar population models using such libraries as input to the M05 code.

Several libraries of empirical stellar spectra are available, e.g. Pickles (1998, hereafter P98), STELIB (Le Borgne et al. 2003), MILES (Sánchez-Blázquez et al. 2006) and ELODIE.v3.1 (Prugniel et al. 2007). For the aim of this work, which is to study the redshift evolution of broad-band colours, the Pickles library is the only suitable one, due to its wide wavelength coverage (1150–25 000 Å). The mapping of stellar atmospheric parameters in the Pickles library is very good, especially for the lower main sequence and the tip of the red giant branch. The library does not contain enough stars to cover all important evolutionary phases for non-solar metallicities. Therefore, this exercise focuses on models with solar metallicity, the most relevant for massive galaxies such as LRGs.

Models constructed from other libraries have also been computed, which will be described in future publications. We will use these models at zero redshift in order to assess consistency between the various empirical libraries.

The effect of the input stellar library is shown in Fig. 3, which displays the spectral energy distributions (SEDs) of 12 Gyr, solar metallicity SSP models that differ only in their input spectral library. The red line shows the one based on the P98 empirical library, whereas the black one is based on the Lejeune et al. (1997) theoretical library. A flux excess is evident in the theoretical spectrum between ∼5500 and ∼6500 Å (as normalized to 5050 Å). The models based on the MILES and the STELIB libraries confirm the effect. Note that in case of the STELIB library, we implemented the missing cool dwarf component using the Main Sequence dwarfs from P98. Note also the fall of flux displayed by the MILES-based SSP longward 6200 Å. This is due to the specific spectra of cool giants in this library (see also Fig. 4, lower left panel), an issue that will be addressed in a future publication.

To gain insights into this discrepancy, we plot in Fig. 4 the individual stellar spectra from various libraries. Left-hand panels show the spectra of giant stars, at the bump and the tip of old, metal-rich stellar populations. The bump is a location where much fuel is burned (M05). The right-hand panels show two typical turnoffs of

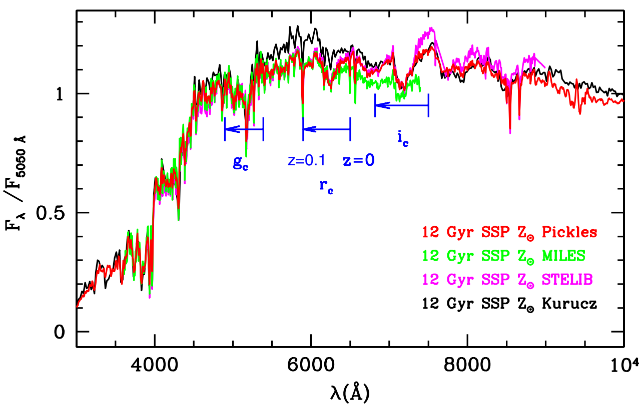

Figure 3. The effect of the input spectral library. The SEDs of 12-Gyr-old, solar-metallicity SSPs using theoretical (black) and empirical (red from Pickles 1998; green from MILES and magenta from STELIB) spectral libraries. The STELIB and MILES spectra are smoothed for the Pickles resolution. Note the flux excess in the theoretical spectrum between ∼5500 and ∼6500 Å. Also shown are the central wavelengths of the *g*, *r*, *i* SDSS filters at redshift 0 and 0.1. The lower flux in the MILES library at larger wavelength is due to the specific spectra of cool giants in this library (see Fig. 4, bottom left panel).

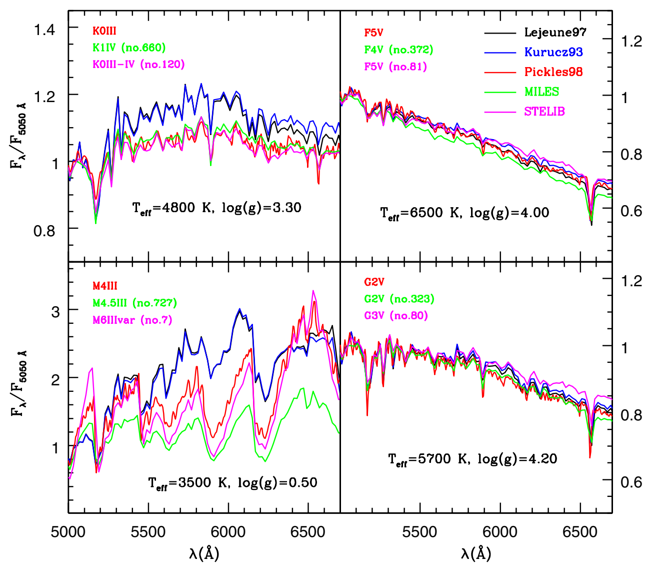

Figure 4. Comparison of stellar spectra from different libraries, for key temperature/gravity locations. Left-hand panels display giant stars at the bump (upper panel) and the tip (lower panel) of the red giant branch. Right-hand panels show the turnoff of a 3 Gyr (upper panel) and an 11 Gyr (lower panel) stellar population model with solar metallicity. The STELIB and MILES spectra are smoothed to the Pickles resolution.

3- and 11-Gyr-old populations with $Z_{\odot}$. For the empirical spectra from P98, we print the spectral types; and for the MILES and the STELIB ones, we quote the star reference number.

The individual stellar spectra show the same effect as the integrated model. The discrepancy increases with decreasing effective temperature. Cool dwarfs (not shown) display the same effect, hence the mismatch is not much dependent of gravity. It also disappears in warm turnoffs. Therefore, in the synthesis models, the effect is going to be prominent for old and metal-rich populations. A similar problem was reported by Worthey (1994), who found that the spectra of giant stars in the Kurucz library are the cause for a discrepancy between synthetic $B - V$ colours of stellar populations and star clusters. A similar comment is given in M05. From Fig. 4, we also see that the source of the discrepancy does not lie in the rescaling of the Kurucz spectra performed by Lejeune et al. as the two spectra agree in this wavelength range.

The MILES and the STELIB stars display a very similar behaviour to the Pickles ones. This leads us to conclude that empirical stars have a lower normalized flux in the noted ∼5500–6500 λ-range than model stars.

We can now understand the net effect on the population synthesis models. In Fig. 3, we show the central wavelengths of the g, r, i SDSS filters at redshifts 0 and 0.1. The lower flux in the empirical spectrum is sampled by the r-filter at redshift 0.1, which explains the redder $r - i$ colours (by ∼0.06 mag) of the Pickles-based models with respect to the theoretical ones. For the same reason, the $g - r$ at $z = 0.1$ is bluer by ∼0.05 mag. The comparison with SDSS data is shown by the middle panels of Figs 1 and 2. The inclusion of the empirical library rectifies the position of the models with respect to the data at the lowest sampled redshift. The predicted $g - r$ colour becomes bluer and the $r - i$ colour redder around $z \sim 0.1$. The trend is the opposite at higher redshifts; the observed frame $g - r$ colour gets redder and the $r - i$ colour slightly bluer around $z \sim 0.6$. Hence, the model has improved mainly at lower redshifts, and most significantly in the $r - i$ colour. Further modifications to the model are still necessary to track correctly the evolution with redshift. However, the situation has become much clearer with the inclusion of empirical atmospheres.

3.2 The metal-poor subcomponent

As the middle panel of Fig. 1 shows the match between models and data still requires a slightly bluer $g - r$ colours at low redshift, and both bluer $g - r$ and $r - i$ colours at high redshift. The flatness of $g - r$ beyond $z = 0.4$ suggests that the required bluening component must be slowly evolving with look-back times. This disfavours residual star formation (see W06 and Section 3.3). A metal-poor old subcomponent is the best candidate.

Metal-poor stellar populations have blue turnoff's and very often blue horizontal branches (BHBs). A BHB from a metal-poor stellar population arises due to the relatively high effective temperature of the evolving stars, even without assuming large amount of mass loss during the red giant branch phase. Calculations show that a stellar population with metallicity [Z/H] ~ -2.2 develops a BHB already at ages of ∼6 Gyr (fig. 11 in M05.)

The difference in SEDs between a solar-metallicity model and the same contaminated by metal-poor stars (3 per cent in mass) is such that the composite SED has more flux in optical bands, while leaving unaltered the flux longward ∼9000 Å (Maraston & Thomas 2000). This helps the $g - r$ colour to become bluer without perturbing the $r - i$ colour at the lowest redshifts. At the highest redshifts, it makes both colours bluer as required by the data.

As mentioned above, components of metallicities other than solar cannot be based on the empirical spectral library of Pickles. The metal-poor subcomponent is therefore taken from the original M05 model based on theoretical stellar atmospheres. We checked that the MILES- and the Lejeune-based SSPs compare very well at such low metallicity of −2.2.

The final composite solution and the colour residuals are shown in the right-hand panels of Figs 1 and 2. The redshift evolution of the SDSS data is now well matched by the model in both the $g - r$ and $r - i$ colours with a residual discrepancy of only 0.02 mag in $r - i$ around $z \sim 0.3$.

3.3 Discussion of other options

Alternative metallicity models have been tried, but none of these performs better than the working model (based on the residuals). For example, using a slightly higher percentage of a less metal-poor population with [Z/H] ~ -1.3 gives a fair match, but the residuals have a worse χ^2. This is due to the fact that one needs the differential effect of bluing the optical spectrum shortward ∼5500 Å while leaving unchanged the flux at longer wavelengths. For the same reason, a single model with slightly subsolar (e.g. half-solar) metallicity is not a viable solution.

The inclusion of a BHB in the metal-rich component is less attractive, as a quite large fraction of the population would need to develop a BHB.

We also tested the possibility of including recent star formation on top of the passively evolving SSP based on the Pickles stellar library. We included a small subcomponent with constant star formation rate since $z = 5$ summing up to a mass fraction of 3 per cent at $z = 0$. We confirm that the bluing of observed frame $g - r$ becomes too large around $z = 0.6$ with respect to $z = 0.1$. This effect could be avoided only by assuming that the level of residual star formation in LRGs has been increasing steadily at least since redshift $z = 0.7$, which seems contrived.

Finally, LRGs host α/Fe-enhanced stellar populations (Eisenstein et al. 2003; Bernardi et al. 2006) and our stellar population models are solar scaled, which in principle is not correct. However, it has been recently shown that an enhanced [α/Fe] ratio has virtually no effect on stellar evolutionary tracks (Dotter et al. 2007). Instead, studies based on theoretical stellar spectra (Coelho et al. 2007; Lee et al. 2008) find that the [α/Fe] enhancement does affect optical broad-band colours such that both $g - r$ and $r - i$ become bluer. Such an effect therefore cannot substitute the empirical library, but could, in principle, mimic the addition of a metal-poor subcomponent.

We make a rough estimate of the effect. LRGs have typical [α/Fe] $\sim +0.2$ (Bernardi et al. 2006). From Coelho et al., we estimate that this leads to a bluing of ∼0.15 mag in the rest-frame $u - g$ and ∼0.05 mag in the rest-frame $g - r$ at a fixed total metallicity and an age of 11 Gyr. This effect is significantly larger than the offset between the Pickles-based model and data (middle panel of Fig. 1). In fact, the addition of a metal-poor population in the best working model results in a bluing of the observed $g - r$ and $r - i$ (at $z \sim 0.1$) by only ∼0.025 and ∼0.010 mag, respectively.

4 CONCLUSIONS

We provide a working stellar population model for LRGs, which allows a substantial improvement to a long-standing mismatch with the data from the SDSS (Eisenstein et al. 2001; W06). The new model adopts empirical stellar spectra from the library of Pickles

(1998) in place of the theoretical ones at solar metallicity in the evolutionary population synthesis. We found that an excess flux around 6000 Å with respect to 5000 Å (rest frame) in the theoretical spectra was responsible for making the synthetic $r - i$ colour too blue at redshift 0.1, and the $g - r$ colour too red. The same effect is found in stellar population models based on other empirical libraries such as MILES and STELIB.

This finding impacts on a variety of studies which involve the $B - V$ and $V - R$ rest frame. The new model further includes the addition of a small (3 per cent by mass), metal-poor subcomponent, being coeval to the old and metal-rich dominant population. The metal-poor old subcomponent can better match the observed colour and colour evolution because of its slow evolution with redshift in comparison to a young subpopulation, whose colour evolution is much stronger. This model was constrained using data in the redshift range 0.1 to ∼0.8.[1] The conclusion that local elliptical galaxies require a very small mass component with metallicity below ~ -1 was reached by Worthey, Dorman & Jones (1996), Lotz, Ferguson & Bohlin (2000) and Maraston & Thomas (2000), to which we refer for a wider discussion. Here, we add that such effect is required up to high look-back times. It needs to be assessed whether the requirement for such a component reflects the metallicity gradients known to be present in massive galaxies or is indeed caused by the presence of a very metal poor subcomponent. The latter could originate from accretion of metal poor dwarf satellites during the evolution of the galaxy. Future investigations on this question will be very valuable.

The models are available at www.maraston.eu.

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[1] An early version of this model was used in Cool et al. (2008) for studying the luminosity function up to a redshift 0.8. Though the model allowed us for a better match towards the highest redshifts, the synthetic $g - r$ was still too red at the lowest redshifts (cf. fig. 13 in Cool et al. 2008), and the $r - i$ was not well recovered. This early model did not include the empirical spectra. For this reason, a larger metallicity for the dominant population needed to be assumed, and as a consequence a higher fraction by mass of metal-poor stars. The use of the empirical spectra has solved the remaining problems.

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