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Comparative Studies of Population Synthesis Models in the Framework of Modified Strömgren Filters

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Abstract. Evolutionary models form a vital part of stellar population research in understanding their evolution, but despite their long history of development, they are often misrepresented and the properties of stellar population observed through broadband and spectroscopic measurements are also misinterpreted. With growing numbers of these synthesis models, model comparison becomes an important analysis to choose a suitable model for understanding stellar populations and model up-gradation. Along with model comparison, we reinvestigate the technique of modified Strömgren photometry to measure reliable parameter-sensitive colours and estimate precise model ages and metallicities. The assessment of Rakos/Schulz models with GALEV and Worthey's Lick/IDS model find smaller colour variation: $\Delta(uz - vz) \leq 0.056$, $\Delta(bz - yz) \leq -0.05$ and $\Delta(vz - yz) \leq 0.061$. The study conveys a good agreement of GALEV models with modified Strömgren colours but with poor UV model predictions and observed globular cluster data, while the spectroscopic models perform badly because of outdated isochrone and stellar spectral libraries with inaccurate/insufficient knowledge of various stellar phases and their treatment. Overall, the assessment finds modified Strömgren photometry well suited to study different types stellar populations by mitigating the effects of age-metallicity degeneracy.

Key words. Galaxy: evolution—galaxy: formation—galaxy: general—galaxy: globular clusters: general galaxies: abundance—galaxies: photometry—galaxies: star clusters: general—galaxies: star formation.

1. Introduction

Stellar Population Synthesis Models (PSMs) – a vital tool to understand stellar systems such as globular clusters and galaxies – provide insights to Star-Formation History (SFH), stellar metallicity (Z) and individual elemental abundance pattern,

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stellar Initial Mass Function (IMF), total mass in stars, dust and gas content. These properties are extracted from the Spectral Energy Distribution (SED) of stellar systems, formed from the library of theoretical isochrones (with signature L, T_{eff}, initial chemical composition and mass M of individual stars) and the library of stellar spectra with the aid of stellar evolutionary theory. To this integrated spectrum corrections are applied, if needed, due to dust, nebular emission and K-correction. Eventually magnitudes/colours, chemical composition based on the line strength of the indices are measured from the resulting spectrum (Salaris *et al.* 2009) which relate to different scenarios of the evolution of galaxies and galaxy clusters which cannot be resolved due to their individual stellar types.

The history of stellar population modelling dates back to the attempts by Crampin & Hoyle (1961) by correlating the observed B–V with M_V for various ages by assuming a constant Red Giant Branch (RGB) tip and homology of isochrones. With the first set of wide evolutionary tracks, Tinsley (1968) introduced the first set of synthesis models, while Spinrad & Taylor (1971) reproduced the observed integrated light of stellar populations by trial-and-error method of combining of the stellar spectra of different classes. Tinsley (1972a, b, 1973) detected the spectrophotometric properties, approximate analytical solutions to Star Formation Rates (SFRs), chemical compositions and IMFs to give an evolutionary perspective from visual and Near-Infra Red (NIR) colours. Models by Gunn *et al.* (1981), which included empirical RGB, Asymptotic Giant Branch (AGB), lower-Main Sequence (MS) phases and isochrones with uncalibrated mixing length of different stellar phases, badly failed to reproduce the MS stars of the galactic Globular Clusters (GCs) and miscalculated the ages of ellipticals (by a few giga years). This took population synthesis modelling back to the drawing board. Models developed since then focussed meticulously on co-evolving, chemically homogenous stars – the so-called Single Stellar Populations or SSPs – including isochrones with calibrated mixing lengths and accounting proper energy contribution of different stellar phases. Also, in this era, the models spanned a wider range in age and metallicity to include Horizontal Branch (HB), AGB, post-AGB phases. By 1990s, isochrone synthesis technique had become popular, which led models by Bruzual & Charlot (1993) and Charlot & Bruzual (1991) to refine colour variations and include the semi-empirical analysis of Thermally Pulsating-AGB (TP-AGB) phase. This advancement resulted in ages to extend below 1 Gyr (for $Z = Z_{\odot}$), and paved a platform for a new generation of isochrone synthesis by Geneva (Tantalo *et al.* 1996) and Padova (Leitherer *et al.* 1999). Subsequently, other models were also developed by Worthey (1994, W94 henceforth), Worthey *et al.* (1994), Vazdekis *et al.* (1997) and Vazdekis (1999). These models set a new trend to offer a whole suit of features, for e.g. colours, spectral energy distributions, mass-to-light ratios, spectral indices, surface brightness fluctuations, metallicities, ages, IMFs, etc. These types of models were termed as the comprehensive models (Maraston 2003).

Now there are a myriad number of stellar population models (Arimoto & Yoshii 1986, 1987; Buzzoni 1989; Bruzual & Charlot 1993; Bressan *et al.* 1994) in the scientific community, amongst which, the latest classification (Chen *et al.* 2010) includes models with a library of empirical spectra of stars and star clusters, termed as the empirical population synthesis models (Faber 1972; O'Connell 1976; Pickles 1985; Bica 1988; Boisson *et al.* 2000; Cid Fernandes *et al.* 2001), and, the other is the conventional, Evolutionary Population Synthesis models (EPS; Tinsley 1978; Bruzual 1983; Worthey 1994; Leitherer & Heckman 1995; Maraston 1998; Vazdekis & Arimoto 1999; Bruzual & Charlot 2003; Maraston 2005; Cid Fernandes *et al.* 2005). This set of eps models uses the knowledge of stellar evolution to model the spectrophotometric properties of stellar populations. In empirical models, the observed spectrum of a galaxy is reproduced by a combination of spectra of individual stars and stellar populations with different ages and metallicities from a library. Whereas, in EPS models, the spectrum of an individual stellar population or galaxy is formed by the combination of several stellar population spectra by adjusting parameters like the stellar evolutionary tracks, stellar spectral library, IMF, SFH and the grids of ages and metallicities.

These PSMs have greatly benefited our understanding of stellar structures as a function of time, chemical composition and IMF. Besides their paramount importance of reproducing the integrated light of resolved SSPs, they are also important in interpreting unresolved stellar populations with unknown SFH, if the model hosts a bigger archive of SSP spectra covering a large range of ages and metallicities (like galaxies, starbursts, galaxy groups and clusters), with linear combination of input spectra (Schulz *et al.* 2002; S02 henceforth). PSMs are also helpful in understanding the cosmological structure formation scenario, if individual galaxies were built from sub-galactic fragments to a state resembling the Milky Way in several aspects (Contrado *et al.* 1999).

However, despite decades of history in developing and improving these PSMs, several critical caveats are still observed that constrain correct measurement of stellar population properties like:

(1) the behaviour and contribution of several stellar evolutionary phases like the TP-AGB, blue-stragglers, convective core overshoot, helium abundance (specially at higher metallicities) etc., are not well known, but their effects create enormous ($\sim$1–2 mag) model divergence from the observed – a serious issue to be corrected in isochrones;
(2) almost all spectral libraries archive spectra of low resolution which results in an uncertain estimation of chemical composition and age. In order for these models to measure the strength of numerous weak absorption lines and strong lines over a wide range of ages, high resolution spectral libraries are urgently needed;
(3) the study of galaxy formation and SFH, along with age, would clearly be based on observations of nearby galaxies (Worthey 1994), but the Z effect masks the age effect. This results in erroneous age and/or Z measurements, the so-called age-metallicity degeneracy (Worthey 1999). A model which can break this degeneracy to give precise ages and metallicities is required;
(4) the limited range of parameters and their combinations, especially of age and Z, introduces problems in linear interpolation and extrapolation to higher and lower orders. This range needs to be extended;
(5) Salaris *et al.* (2009) pointed out the lack of a single theoretical (or empirical) spectral library, covering all relevant parameter space.

In an attempt to constrain some of these errors, flaws and model divergence, Rakos & Schombert (2005; RS05 henceforth) developed a semi-empirical population synthesis model by incorporating Schulz *et al.* (2002; S02) with the application of the Principle Component Analysis (PCA; Steindling *et al.* 2001; S01) to suit their novel modified Strömgren filters (Fiala *et al.* 1986; Rakos *et al.* 1988, 1990; discussed in section 2.3).

Prior to adopting a new set of improved models (to further resolve model errors), as an objective of this paper, we perform a model comparison study of RS05 with, one which is fairly new (2009) and, the other, that is carefully studied using the Lick indices. This assessment aims to check for reliability and reproducibility of the modified Strömgren colours to compare with different models and re-investigate the filter transmission curves of the modified Strömgren filters by agreement of convolved colours with those of model SSPs. This would verify the technique's ability to study stellar population properties of single and composite nature.

Although there are several others, which are much more improved and comprehensive EPS and empirical models, in order to keep our current study straightforward and vital, we chose to probe with the established and thoroughly analysed models. Nevertheless, new models like the Flexible Stellar Population Synthesis (FSPS; Conroy *et al.* 2009, 2010) and STARLIGHT (Cid Fernandes *et al.* 2007, 2013), are currently being assessed and would be addressed in our subsequent paper. But for our current study, as a fairly new model, we opt for GALEV (Kotulla *et al.* 2009; K09) – successor of S02 models – which include new features of latest evolutionary tracks, better treatment of TP-AGB and convective overshooting phases while offering a more comprehensive output (discussed in section 2.1). From the Lick/IDS perspective, we chose W94 (elaborated in section 2.2) models which are based on reliable stellar evolutionary isochrones from VandenBerg and collaborators and the Revised Yale isochrones (Green *et al.* 1987) with proper accounting of errors in the estimation of age, metallicity and IMF (W94). For this comparison, we arrange this paper with comparison components describing Schulz and GALEV models in section 2.1, the Lick/IDS systems in section 2.2, Rakos's modified Strömgren filter systems in section 2.3, the comparison method of models in section 3. Finally in section 4, we reiterate with conclusions.

2. Comparison components

2.1 *Schulz/GALEV population synthesis models*

The Gottingen group of S02 devised a SSP-based PSMs with the metallicity range of $0.02 \leq Z/Z_{\odot} \leq -2.5$ and age range of 4×10^6 yr $\leq t \leq 16$ Gyr. They use the Padova group isochrone library with TP-AGB stars in the range of $2M_{\odot} \leq M \leq 7M_{\odot}$ and stellar atmosphere spectral library from Lejeune *et al.* (1997, 1998). Lejeune *et al.*'s single burst star-formation model libraries are in the wavelength range of 90 Å to 160 μm, which they claim to be complete in terms of stellar effective temperature from $T_{\rm eff} = 2800-47500$ K, and surface gravities from $-1.0 \leq \log g \leq 5.5$.

However, poor resolution of S02's spectra are of the order of 20 Å in the wavelength range 3000–10000 Å and beyond that, even worse, to 50 Å. This poor resolution hinders an in-depth analysis of individual line indices. Spectral comparison between various models shows very poor agreement for wavelengths below 2000 Å, where the major contributors are hot stars and cool white dwarfs. Another drawback in this PSM comes from the use of broadband colours in measuring age and metallicity, which are highly contaminated with age-metallicity degeneracy (Worthey 1999). This would result in colour discrepancy between the model spectra and the observed values. Most PSMs, including S02, have a limited range of *Z* values based on the Milky Way or M31 GCs.

GALEV (K09) offers users many features, one of which is its chemically consistent models, such that a stellar spectral evolution could be studied with the evolution of chemical composition of InterStellar Medium (ISM). Yet another GALEV's ingenious feature is its very informative output on spectra, emission and absorption line indices, photometric magnitudes/colours for a range of filter systems, chemical abundances, gaseous and stellar masses, SFR in their time evolution of normal, starburst galaxies and galaxies with truncated SFR. However, they still use the same spectral and isochrone libraries as S02 models and, hence, remains the poor resolution of 20 Å for UV-optical and 50–100 Å in the NIR (near-IR) wavelength.

Even after such careful up-gradation from S02 to GALEV, there are still discrepancies in the observed and modeled spectra. From Fig. 8 in K09, that displays the comparisons of model spectra with the local templates for different (Hubble) galaxy types from the Kennicutt (1992) catalogue, one can notice significant differences in each galaxy type spectra amongst differently coloured templates. Agreeably, these differences are indeed small, with an average maximum of the relative difference of 0.3 (refer Fig. 8 in K09) for most galaxy types up to $\lambda = 4500$ Å, which comprise two of our special Strömgren filters, namely *uz* (3500 Å) and *vz* (4100 Å). Similar order differences are also observed in our colour estimations of the modified Strömgren photometry (discussed in section 2.3).

2.2 *Spectroscopic Lick indices*

An extensive work on these PSMs has been done by W94, which includes comparison of modeled line indices and observed spectroscopic methods. W94 pointed out that these models assume exactly one age and one *Z* for an entire stellar population, hence, one-to-one comparison of galaxies is not possible. In reality, however, galaxies are composite in *Z* (at least) and age. Furthermore, models also assume that the HB stars remain in the red clump of the giant branch, but that is not the case for metal-poor stars. Observations have confirmed that galaxies with metal-poor stars indeed show extended horizontal branches. However, models that could compare and successfully match the observed phenomenon in CSPs are eagerly awaited.

Age-metallicity degeneracy is a long-standing problem in galaxy evolutionary studies and W94 suggested that one possible way to separate age effects from metallicity effects is by using respectively sensitive colours and/or line indices. Any variation in a particular line index by an amount ΔI (refer Table 6 in W94) could be explained either due to change in age or change in metallicity. W94 also conveys that the most commonly used *Z* and age sensitive line indices are often contaminated by indices of other elements.

2.3 *Modified Strömgren Photometry*

In principle, the modified Strömgren filters, denoted as *uz*, *vz*, *bz*, *yz* (where *z* represents their red-shifted nature), are not much different from the normal Strömgren

(u, v, b, y) filters, as the effective wavelengths of the two filter systems are almost same. However, the modifications in the modified Strömgren filters come from the following aspects:

(1) The uz filter is slightly (30 Å) shifted to the red to focus more on the red galaxies.
(2) The calibration of these filters is performed using spectrophotometric standard stars which are shifted to the redshift of the target cluster Rakos *et al.* (1988). This makes the zero point of the magnitudes differ along with the cluster's redshift.
(3) The flux measurement for the galaxies and the standard stars is in wavelength units (per Å), as is usual for most galaxy studies instead of frequency (per Hz) units – as in the stellar studies (Sreedhar *et al.* 2012).

These modified Strömgren filters were initially designed by Fiala *et al.* (1986) and later used by Rakos & Schombert (1995) to study galaxies in clusters. Figure 1 shows the similarity of Strömgren and modified Strömgren filter transmission curves. The modified Strömgren filter system covers three regions in the near-UV and one in the optical blue portion of the electromagnetic spectrum. The bz ($\lambda_{\mathrm{eff}} = 4675$ Å) and yz ($\lambda_{\mathrm{eff}} = 5500$ Å) focuses on the continuum part of the spectrum, both of which combine to form the temperature–colour index $(bz-yz)$. Filter vz ($\lambda_{\mathrm{eff}} = 4100$ Å) is strongly influenced by the metal absorption lines (i.e. Fe, CN) from old stellar populations, whereas uz ($\lambda_{\mathrm{eff}} = 3500$ Å) is shortward of the Balmer jump.

These filters are narrow enough to ensure spectral purity and passbands which are well placed to study the Balmer discontinuity and the spectral continuum covered by our bz and yz filters. The idea is to look for the change in colour of the RGB, that acts as a metallicity indicator, and similarly, change in colour, produced by shifting the turnoff points, which reflects the age (Tinsley 1980) in galaxies.

Since broadband colours are not well suited for separating age effects from metallicity effects, Rakos & Schombert (1995, 2005, 2007), Rakos et al. (2001) attempted to solve the age-metallicity degeneracy problem uniquely by using narrow-band colours with the PCA technique. The PC analysis is a three-dimensional multicolour space defined by these modified Strömgren colours and is formed by three PC equations (refer S01), where different Hubble type galaxies take selected places in that cluster-box.

Acceptable linearity for ages greater than 3 Gyr over a full range of metallicities, needed for application of these PC analysis, were found with S02 models (RS05). Interpolation between the model grids were performed by well-studied GCs (shown in Fig. 2) using the modified Strömgren photometry, hence, referred as the semi-empirical models. The original S02 models offer a carefully calibrated Strömgren magnitude (Gray 1998) for a set of metallicity values for a range of ages, that are transformed to modified Strömgren filter system using the following equations from Rakos *et al.* (1996):

$$(bz - yz) = -0.268 + 0.973(b - y), \tag{1}$$

$$mz = 1.092m_1 - 0.017(b - y), \tag{2}$$

$$cz = 0.234 + 1.034c_1 - 0.152(b - y), \tag{3}$$

where, m_1 and c_1 are the old Strömgren metal-line and surface gravity indices, respectively, given by

$$m_1 = (v - b) - (b - y) \tag{4}$$

$$c_1 = (u - v) - (v - b) \tag{5}$$

These modified Strömgren colours are tabulated in RS05, and here in columns 3–5 of Table 1 for comparison. The ages and metallicities estimated using these semi-empirical models are found to have errors of 0.2 dex in Z and 0.5 Gyr in age.

Acknowledging the inaccurate and incorrect model estimates, Rakos and co-workers took careful measures in order to prevent and/or curb these model divergence benefiting these modified Strömgren colour indices which show sensitivity towards metallicity, dust, 4000 Å break and age of the underlying populations, which are discussed in different articles. In Rakos *et al.* (1990), a direct, empirical relation to [Fe/H] (between $-2.1 < \text{[Fe/H]} < 0$) using $(vz{-}yz)$, $(bz{-}yz)$ for SSPs and CSPs are drawn. In Rakos *et al.* (2001), this relation was updated for a much tighter one using the $vz{-}yz$ index with observations of the 41 Milky Way GCs and Fornax dwarf ellipticals (using spectroscopic measurements by Held & Mould 1994). In Rakos & Schombert (2004), this updated relation is compared and

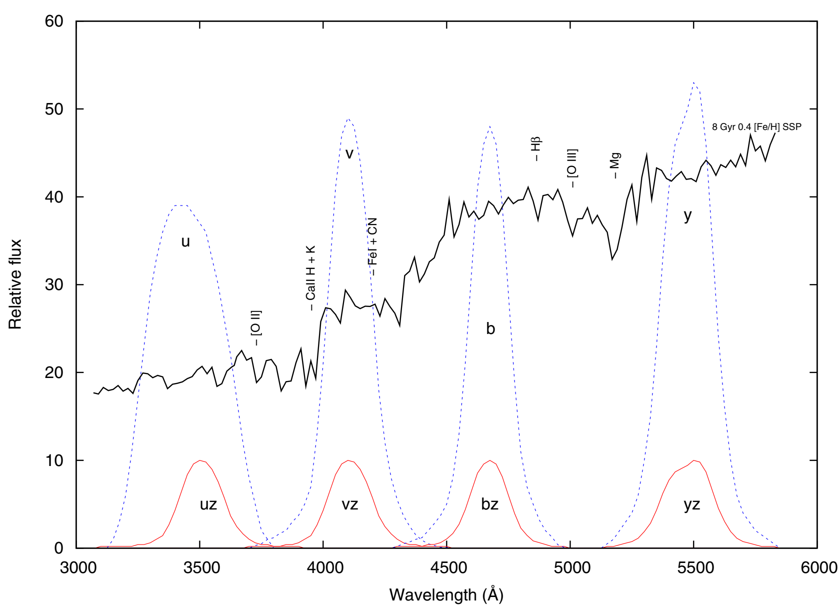

Figure 1. The two sets of filters, Strömgren and modified Strömgren are displayed in *dashed* and *solid lines*, respectively with 8 Gyr 0.4 [Fe/H] SSP spectra from W94 in the background. The four filters of either systems are concentrated at *u* (3500 Å), *v* (4100 Å), *b* (4675 Å), *y* (5500 Å) to investigate the narrow regions of the spectra, essential for studying specific parameters of stellar population. Modified Strömgren are on average narrower (20 Å) than the conventional Strömgren filters and are redshifted to the target cluster.

Table 1. The comparison presents the colours of different SSP models of different ages and metallicities of the modified Strömgren colours between Rakos (RS05) with GALEV (K09) and spectroscopic Lick/IDS (W94) studies.

Z dex	Age (Gyr)	RS05 (*uz*−*vz*)	RS05 (*bz*−*yz*)	RS05 (*vz*−*yz*)	GALEV (*uz*−*vz*)	GALEV (*bz*−*yz*)	GALEV (*vz*−*yz*)	W94 (*uz*−*vz*)	W94 (*bz*−*yz*)	W95 (*vz*−*yz*)
−1.7	3	0.73	0.12	0.03	0.71	0.13	0.03			
−1.7	4	0.69	0.14	0.07	0.66	0.15	0.08			
−1.7	6	0.65	0.17	0.12	0.61	0.18	0.14			
−1.7	8	0.62	0.18	0.14	0.58	0.19	0.15	0.596	0.144	−0.090
−1.7	10	0.6	0.19	0.16	0.57	0.2	0.17	0.592	0.162	−0.052
−1.7	12	0.61	0.19	0.17	0.56	0.21	0.18	0.588	0.177	−0.021
−1.7	14	0.62	0.2	0.18	0.58	0.21	0.18	0.591	0.189	0.006
−0.7	3	0.72	0.21	0.31	0.71	0.21	0.3			
−0.7	4	0.72	0.22	0.32	0.69	0.22	0.32			
−0.7	6	0.71	0.23	0.36	0.68	0.24	0.37			
−0.7	8	0.73	0.26	0.43	0.7	0.26	0.43	0.659	−0.040	−0.074
−0.7	10	0.73	0.26	0.44	0.71	0.27	0.44	0.669	0.181	0.163
−0.7	12	0.76	0.28	0.49	0.73	0.28	0.49	0.677	0.362	0.356
−0.7	14	0.76	0.27	0.48	0.73	0.28	0.49	0.693	0.501	0.511
−0.4	3	0.74	0.23	0.35	0.71	0.23	0.37			
−0.4	4	0.72	0.23	0.38	0.69	0.23	0.37			
−0.4	6	0.73	0.26	0.44	0.72	0.26	0.44			
−0.4	8	0.77	0.28	0.51	0.75	0.28	0.52	0.686	0.135	0.208
−0.4	10	0.79	0.29	0.54	0.76	0.29	0.54	0.701	0.357	0.450
−0.4	12	0.8	0.29	0.54	0.78	0.29	0.55	0.714	0.539	0.647
−0.4	14	0.83	0.3	0.59	0.81	0.31	0.59	0.731	0.688	0.814
0	3	0.75	0.26	0.46	0.75	0.26	0.46	0.706	0.302	0.422
0	4	0.81	0.29	0.58	0.8	0.29	0.57	0.707	0.304	0.438
0	6	0.78	0.29	0.57	0.81	0.29	0.57	0.723	0.318	0.489
0	8	0.87	0.31	0.65	0.85	0.31	0.64	0.746	0.337	0.550
0	10	0.89	0.32	0.67	0.88	0.33	0.68	0.765	0.347	0.587
0	12	0.95	0.34	0.74	0.94	0.35	0.75	0.780	0.356	0.617
0	14	1	0.35	0.78	0.97	0.35	0.78	0.797	0.363	0.644
0.4	3	0.87	0.29	0.6	0.86	0.29	0.6	0.896	0.335	0.616
0.4	4	0.95	0.33	0.74	0.93	0.33	0.73	0.946	0.361	0.696
0.4	6	1.01	0.33	0.74	1	0.34	0.79	1.006	0.388	0.781
0.4	8	1.06	0.36	0.84	1.06	0.36	0.85	1.039	0.398	0.817
0.4	10	1.11	0.38	0.88	1.1	0.38	0.9	1.090	0.409	0.864
0.4	12	1.13	0.38	0.89	1.14	0.38	0.92	1.131	0.419	0.902
0.4	14	1.21	0.39	0.96	1.19	0.4	0.96	1.161	0.424	0.923

found to fit well with Schulz *et al.* (2002) model metallicities in a colour–colour diagram with M87 globulars. Whereas, the *uz*−*vz* index correlation to the amplitude of spectral [D (4000 Å)] – a parameter-sensitive to the metal content – is shown in Rakos *et al.* (2001). The residual (*bz*−*yz*) shows a good fit with Milky Way globulars and derived isochrone ages from Salaris & Weiss (1998) which is illustrated in Rakos & Schombert (2004). The PCA photometric ages are also compared with Schulz *et al.* (2002) model ages in Rakos & Schombert (2005). In addition, Rakos *et al.* (2001) outline a relation of *vz*−*yz* index with Mg_2 abundance to find that with increasing *vz*−*yz* colour, there is a decrease in [Mg/Fe] ratio – an indirect measure of star formation history. S01 pointed out that since the reddening vector forms at a large enough angle from the effects of age and metallicity, this feature could alleviate the effects of age–dust–metallicity degeneracy (Worthey 1994) by employing PCA technique using rest-frame narrowband colours (Sreedhar 2013).

3. Colour comparison between models and spectroscopy with respect to the modified strömgren filter system

The following comparisons are between the semi-empirical and theoretical models using SSP spectra of different ages and metallicities. Previously estimated colours by RS05 using S02 models (are shown as Rakos/Schulz or RS05), as discussed earlier, are compared with the S02's latest upgrade, GALEV (K09)[1]. Also, in the comparison are the colours from W94's[2] spectra which are convolved using modified Strömgren filter transmission curves.

GALEV colours in the modified Strömgren filter system are estimated by converting Strömgren magnitudes using equations (1)–(3), and applying the zero-point offsets for the Vega system from Gray (1998). The GALEV models offer SSPs for 5 different metallicity values (−1.7, −0.7, −0.3, 0, 0.3 dex) and 6 different ages (3.12, 4.06, 6.02, 10.08, 12.04, 14 Gyr). These GALEV colours are shown in columns 6–8 of Table 1. One important aspect to note here is the small change in metallicity values of ±0.3 dex and ±0.4 dex brought into GALEV from that of S02 models, respectively; this may affect only very negligibly to the colour difference.

Spectra from W94 of similar ages and metallicities as Rakos/Schulz and GALEV are convolved through the modified Strömgren filters transmission curves to obtain their colours, using equations (1)–(3), in the modified Strömgren filter system, these are shown in column 9–11 of Table 1. Blank values in these columns indicate the non-availability of some young, low metallicity SSP spectra – this could be, perhaps, due to the G dwarf problem (van den Bergh 1962; Schmidt 1963).

The table shows close similarities in colours of different ages and metallicities observed between the RS05 and GALEV to testify the reliability of these equations (1)–(3) which transform Strömgren to modified Strömgren colours. While the colours of the W94 spectra show some offset from the RS05 and GALEV models, these offset values between individual model colours, for varying Z and age, are illustrated in Figure 3. But, most metallicity models, displayed in the figure, show points close to the zero mark to convey least offset values. The minimum values in these colour differences are found between the RS05 and GALEV models, whereas the maximum are observed between RS05–Worthey and GALEV–Worthey comparisons. Overall comparison between the three models shows the colour variation as: $0.017 \leq \Delta\, (uz-vz) \leq 0.056$, $-0.004 \leq \Delta(bz-yz) \leq -0.05$ and $-0.004 \leq \Delta(vz-yz) \leq 0.061$.

Figure 2 depicts the model colour tracks in the modified Strömgren photometric system, while the plus symbols show the observed GC colours by RS05, and the ages and metallicities presented by Harris (1996) and Salaris & Weiss (2002); these GC data are shown in Table 2 of RS05. The RS05 and the GALEV model tracks show clear similarities, while the spectroscopic models by W94 strangely present

[1] S02 and the latest GALEV models are obtained from the website: www.galev.org (Kotulla *et al.* 2009).
[2] Spectra can be obtained from http://astro.wsu.edu/worthey/dial/dial_a_model.html

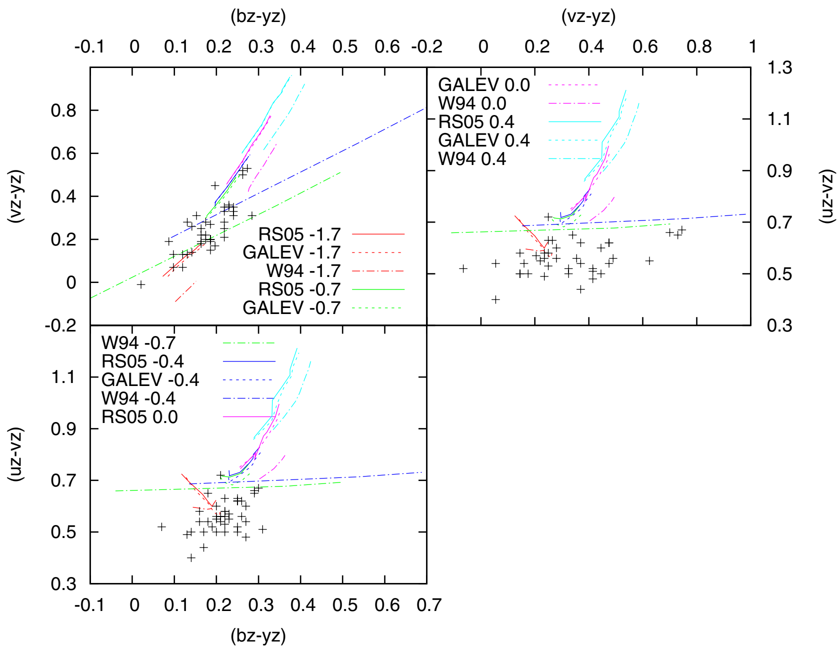

Figure 2. Model colour tracks with observed Globular Clusters. Modified Strömgren colour tracks of different model metallicities and ages for RS05, GALEV, Worthey are displayed and labelled in three different plots. Observed Globular Clusters by RS05 are illustrated with plus signs (these GCs are tabulated in Table 2 in RS05). Clear similarities between the RS05 and GALEV can be seen, while spectroscopic models by W94 are observed to run in different directions. Also, the GC data tend to show a very good agreement with $vz-yz$ and $bz-yz$ model colours of RS05 and GALEV, while $uz-vz$ model colours are much bluer than the observed.

a very different colour behaviour in all three colour plots. The observed colours of GCs are found to agree well with RS05 and GALEV models in the $vz-yz$ and $bz-yz$ colour plots, while being way off in the $uz-vz$ index. Besides the reason of poor (20 Å) spectral resolution of S02 and GALEV models, as pointed out earlier, this disagreement with ($uz-vz$) could be due to poor knowledge and treatment of HB and Blue Stragglers stellar phases at UV wavelengths in most models, as also illustrated by Carter *et al.* (2009) to find the divergence in the GALEV model predictions by 0.05–0.1 mag using broad band filters (Sreedhar 2013). This this sort of divergence is found to be a common problem amongst most models, their correction is an urgent requirement.

Overall deviations in colours of Rakos/Schulz, GALEV with Worthey could possibly be explained by the following reasons:

(1) Colours could deviate by the incorrectly measured metallicities in spectra, due to the contamination of different line indices. Besides that, several other model caveats, as discussed in the Introduction, are also known to affect the model colours.
(2) Differences in colours could also arise due to the limited understanding of theoretical stellar atmospheres and chemical enrichment processes, which could

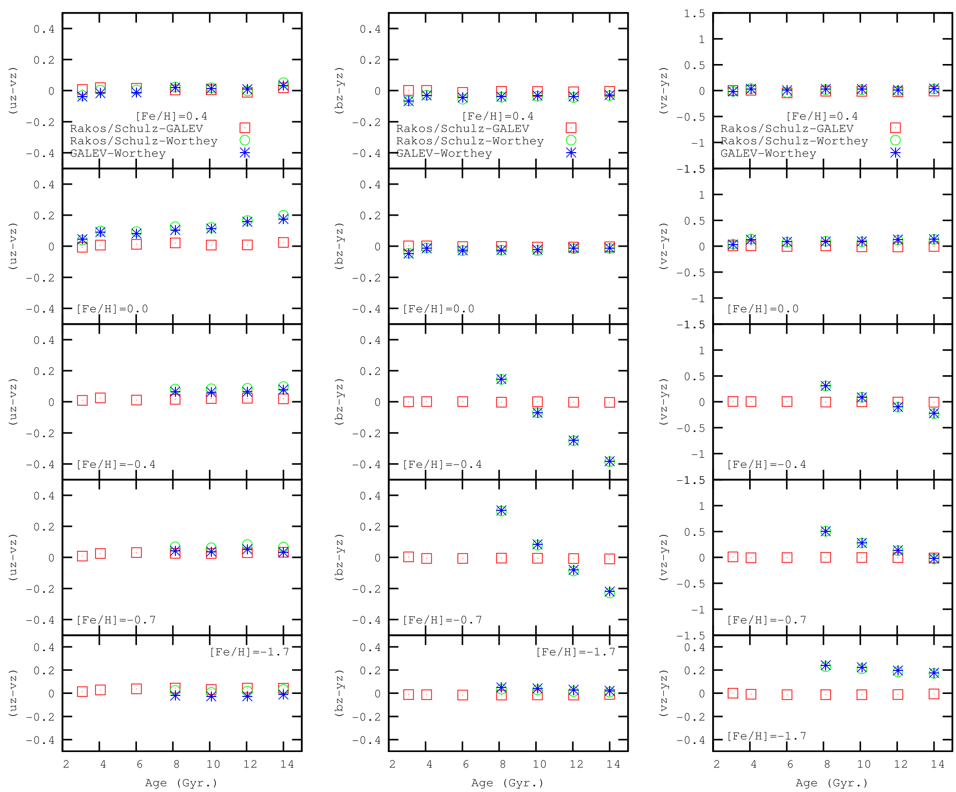

Figure 3. The above plots show the difference in the modified Strömgren colours between the RS05 models with GALEV and W94 for different Zs and ages. Difference between Rakos/Schulz-GALEV are shown in squares, Rakos/Schulz-Worthey in circles, GALEV-Worthey in asterisks. Comparison shows close agreement of Rakos/Schulz with GALEV, however, discrepancy between GALEV-Worthey and Rakos/Schulz-Worthey are observed to be large.

result in the change in spatial pattern of the spectra and, hence, the erroneous colours.

(3) The redder $(vz-yz)$ spectral colours could be explained due to exclusion of low metallicity stars.
(4) The geometrical behaviour of data sampling is also different, such that, slit or fibre spectroscopy that measures the surface brightness of central core regions of a galaxy, instead of integrated light of the whole galaxy as in photometry (Schombert & Rakos 2009). This would in turn result in wrong metallicity measurements.
(5) Minor differences due to convolution of colours by filter transmission curves and small errors due to interpolation between the model grids are also expected to create model divergence.

From the above re-investigation, we conclude that: (1) by the observed similarities in colours (specially in $vz-yz$ and $bz-yz$), the interpolation/modifications performed by RS05 (using S02 models with PCA technique) – to estimate precise ages and metallicities and to reduce the effect of age-metallicity degeneracy – are in good agreement with GALEV and are found to be valid. Therefore, similar interpolation between the GALEV model grids can be utilized in understanding stellar populations. However, like most models, even GALEV presents poor UV predictions for observed stellar populations, which needs to improved vastly; (2) the modification of the modified Strömgren filter system is well designed to accurately study the evolutionary properties of stellar populations of single and composite nature.

4. Conclusions

Considering the importance of PSMs in todays scientific community and their vast numbers that are available, it becomes very difficult to choose an appropriate PSM to incorporate in stellar population studies. Also, as in this case, appropriate PMS are required to suit Rakos's unique (rest-frame, narrow band feature) modified Strömgren photometric technique, that in many ways, are superior to other observational techniques. Therefore, before upgrading the models, we investigate a model comparison with a new (GALEV) and a Lick/IDS study related model (Worthey). This would relate to the technique's reliability of measuring colours and estimating precise model ages and metallicities to study stellar populations. From this study, we infer the following conclusions:

(1) Strömgren colours which are converted to modified Strömgren colours using transformation equations (1)–(3) are found to be valid. These equations produce similar colours for different SSP model ages and metallicities.
(2) A good agreement found between the two (RS05 and GALEV) models conveys GALEV to be a suitable model upgrade replacement. This should also extend the age and metallicity precision to 0.5 Gyr and 0.2 dex, respectively, as shown in RS05 with S02 models.
(3) The modified Strömgren colours obtained by the filter transmission convolution of W94's spectra present offsets by a few hundredths of a magnitude. These differences could be explained due to the differential geometrical observing method of spectroscopy and the redder $(vz-yz)$ colours, due to the exclusion of low metal stars. Also, their poor performance could be because of the use of older isochrone and stellar spectral libraries with inaccurate/insufficient knowledge of various stellar phases and their treatment.
(4) Comparison of model colours with the observed GC data shows that $vz-yz$ and $bz-yz$ indices of RS05 and GALEV models are able to precisely estimate the stellar properties; the model $uz-vz$ colours are found to be bluer than expected – an effect due to poor knowledge and model treatment for the HB and Blue Straggler stellar phases – a rectification that is urgently required.
(5) In conclusion, we find the modified Strömgren filter transmission curves to be well placed in SED to measure parameter-sensitive colours, which are found to agree well with GALEV model colours to measure precise ages and metallicities. This reinvestigation finds the modified Strömgren photometry as a suitable technique to study stellar population properties, of single and composite nature. Latest and improved model comparisons would be assessed in subsequent papers.

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