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A model of population synthesis and the color evolution of galaxies†

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Abstract We construct a model of population synthesis using the new stellar isochrones calculated by Bertelli *et al.* and the observed stellar spectrum from 3130Å to 10800Å by Gunn and Stryker. Our model can predict the spectral energy distribution (SED) of a Simple Stellar Population (SSP) from an age of 10^7 to 2×10^{10} yr with metallicities from $Z = 0.0004$ to $Z = 0.05$, covering the whole optical range. The SED of galaxies at different ages can be derived as a convolution of SSP with corresponding star formation rate at different times. We calculate the standard UBVRI colors as well as 15 medium-band BATC colors for the synthesized SSPs and galaxies. The predicted UBVRI colors of galaxies from E/S0 to Sdm at the age of 12 Gyr are in good agreement with the current observations. So we have some confidence that our model predictions may serve as a theoretical guide for the ongoing multicolor observational study of the SEDs of galaxies.

Key words: galaxy evolution—multicolor photometry

1. INTRODUCTION

Evolution of galaxies can be studies either from the dynamical angle or from the spectrophotometric angle. Dynamical activity usually leads to the formation of stars and star formation rate (SFR) is usually given a simple functional form. Once SFR is given, the luminosity evolution of galaxies with a specific initial mass function (IMF) and chemical composition can be predicted using a model of star population synthesis.

Synthesis models truly based on stellar physics began with the isochrone synthesis (for example, the recent models by Bertelli et al.[1] (BBCFN), Worthey[2] (GW), Bruzual

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& Charlot[3] (B&C) and Refs. [4–12]). There are still large differences among the different models[8], due to different treatments of the internal evolution of the stars and different model atmospheres. The BBCFN model incorporating their main calculation of the isochrones represents the latest level in the modelling of stellar evolution.

One of the objectives of the multi-color sky survey project using Schmidt telescopes centered at Beijing Observatory is to build a spectral energy distribution (SED) library of galaxies based on observations in 15 medium-width color bands and so to authenticate and improve available population synthesis models of stellar evolution. Therefore, it is worthwhile to construct, *ab initio*, a tentative model, which is to be constantly updated in future. A ready objective of our model is to provide a theoretical template for a multi-color photometric study of Abell clusters of galaxies[16]. We have already reviewed population synthesis models in another paper[17]. In this paper, Section 2 describes the model input, Section 3 gives the model estimate for the evolution of a simple stellar population (SSP) and the last section discusses the color evolution of galaxies.

2. MODEL INPUT

We use the isochrones by Bertelli et al.[1], with ages ranging from 4 Myr to 20 Gyr, including various metal abundances. The isochrones were based on calculations of the evolution of stars from $0.6\,M_{\odot}$ to $120\,M_{\odot}$, carried out right to the final stage of the evolution. Because of the use of a new opacity table and a new treatment of mass loss and convective overshoot, these isochrones are better than the Geneva and Yale isochrones[2,3]. Not only is there a delicate interpolation treatment[7], they also include a fine spectral calibration. However, what we needed was the whole SED and not just a few color indices. Also, in order to calculate the SSP for various IMF, the isochrones had to be extrapolated to masses as small as $0.07\,M_{\odot}$[18].

The bolometric correction data required for converting the total luminosity into photometric magnitudes can, in principle, be obtained by putting together all the radiation in all wavelengths. We followed the BBCFN data which were based on the Kurucz model and some actually measured cool stars.

By spectral calibration is meant the assigning of a given SED to a specific type of star. There are many methods of determining the $T_{\rm eff}$ of stars[17]. The B-V color is usually regarded as a good representative of $T_{\rm eff}$, so, by means of a $T_{\rm eff}$ ~(B-V) calibration, we can assign SED to a star on the H-R diagram. Some people use the V-R color. Because of the many methods available it is difficult to decide, in this paper we shall use the MK spectral type to represent $T_{\rm eff}$, this is because 1) it has a physically meaningful basis in the H-R diagram, 2) the spectral features are less affected by reddening, and 3) for late-type stars, B-V is difficult to measure accurately, while the V-K color requires both optical and infrared measurements. Admittedly, this method is not free of problems, arising mainly from the fact that spectral type classification has not been made completely quantitative.

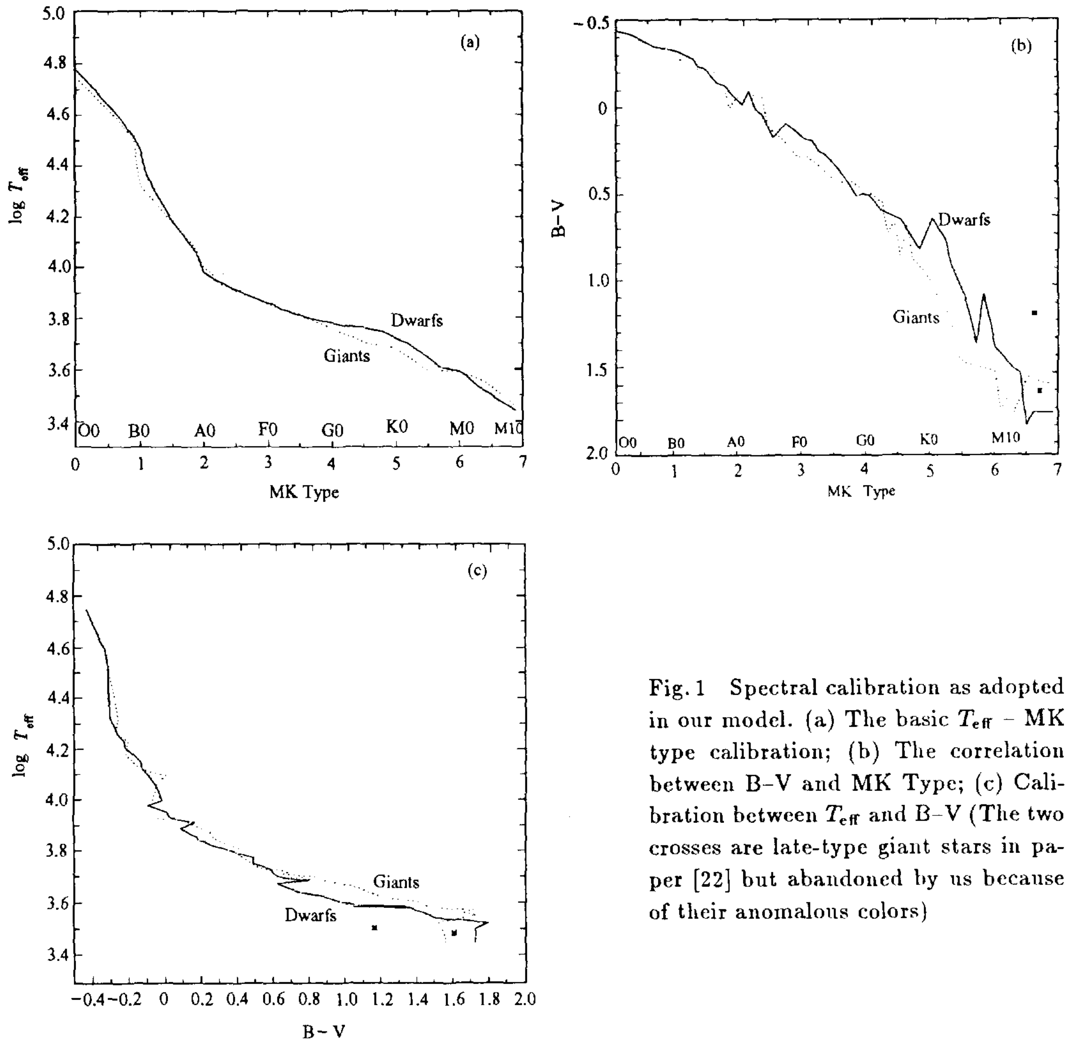

Fig. 1 Spectral calibration as adopted in our model. (a) The basic T_{eff} – MK type calibration; (b) The correlation between B–V and MK Type; (c) Calibration between T_{eff} and B–V (The two crosses are late-type giant stars in paper [22] but abandoned by us because of their anomalous colors)

For the temperature calibration (Fig. 1(a)), the data for the main sequence stars are taken from Refs. [19] and [20], those for the giants, from Refs. [19] and [20], the spectral types O(0-9) through M(0-10) being assigned numbers 0.0–7.0. The calibration also depends on the luminosity class, the giants are redder at type M and bluer at types G and K (Fig. 1(a)). In 1983 Gunn and Stryker[22] compiled an SED library for all types of stars from 3130 Å to 10800 Å, for the specific use of population synthesis, from multi-channel observations with a 5 m reflecting telescope. Although there have been more observations made subsequently[17], the Gunn and Stryker library is still the best (differences of 0.05~0.1 mag in B, A, F type stars have recently been reported[23]). Fig. 1 (or Fig. 2) shows how to assign B-V (or any other color) to a theoretical T_{eff} value. First, we establish the statistical relation between T_{eff} and the MK type (Fig. 1(a)), then, from the observed stars we determined the SED of each MK classification (Fig. 1(b), or Figs. 2(a), 2(c)), hence we get the calibration relation between SED and $T_{\rm eff}$ (Fig. 1(c), or Figs. 2(b), 2(d)). Because there are differences among the observed SEDs of stars of the same MK type, success in modelling in one color will not guarantee success in other colors, so we examined the $T_{\rm eff}$-color relation for the various colors.

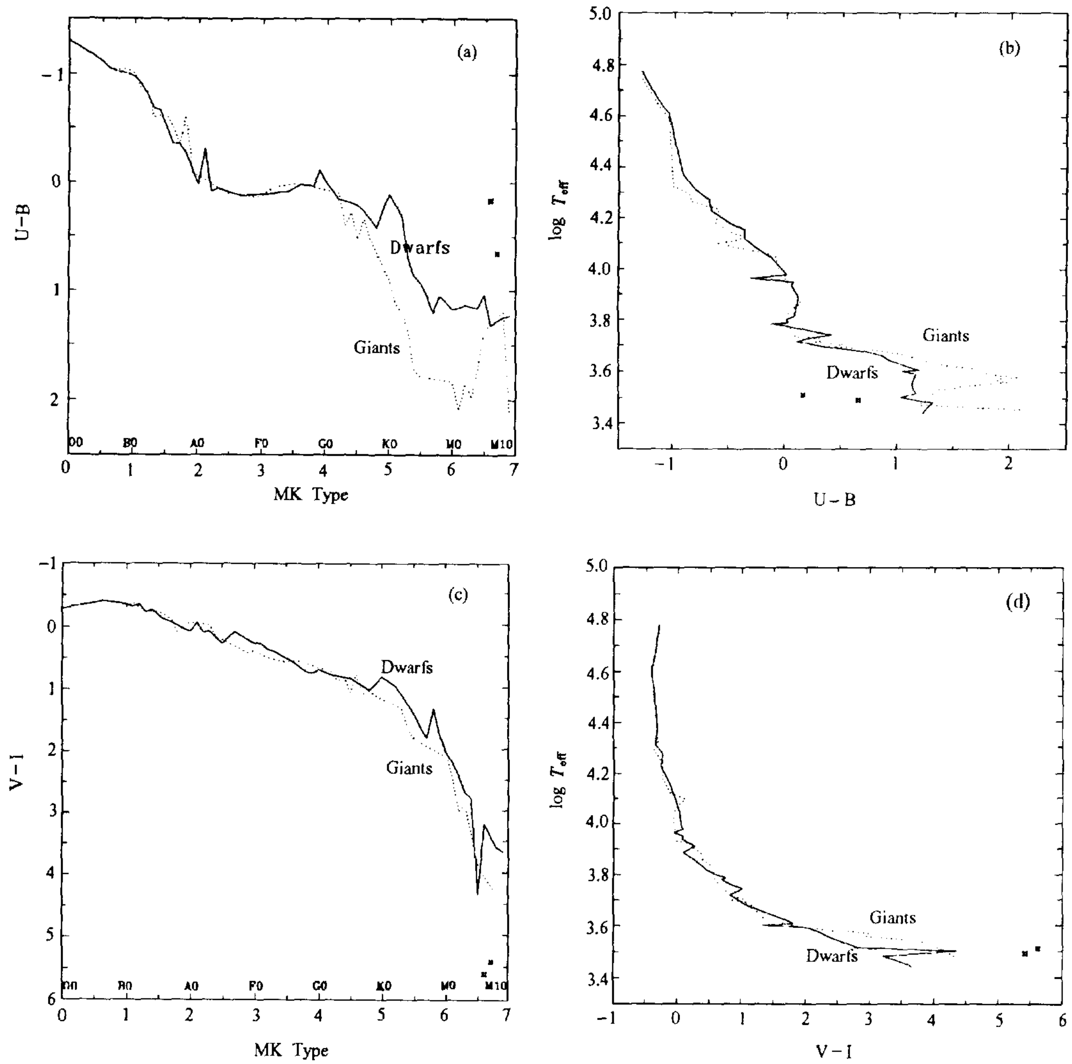

Fig. 2 Spectral calibration in other color bands

Two points should be made. 1) There is no physical reason for believing there should exist violent fluctuations in the calibration curves of Figs. 1 and 2, so, while no smoothing was applied, we yet discarded the two anomalous types M6 III and M7 III. 2) For other metallicities, we still use the calibration for the solar neighborhood; even though the effect of metals is mainly in the interior of the star, their effect in the atmosphere can be as large as 0.3 mag[24].

3. EVOLUTION OF SIMPLE STELLAR POPULATION

Fig. 3 shows that our model (marked Xu) is close to the B&C model and is a little redder. In fact we did hope that our model will not depart too greatly from the previous results. The stellar evolution we used was very different from those used by B&C and GW, and, apart from extrapolation to small masses, was the same as used in BBCFN, and the difference between the two in Fig. 3 comes from using different spectral calibrations, and using a theoretical model atmosphere is more likely to lead to redder colors. In regard to spectral calibration, although B&C also used the Gunn and Stryker calibration, there are differences in many important details, and their Geneva isochrones often lead to bluer colors[8]. The GW model is somewhat out-dated, and our model is closer to B&C and BBCFN in essentials and is not related to GW. For the color of old, elliptical galaxies, the B&C estimates are too blue by 0.03 to 0.1 mag, while the BBCFN estimates are too red. Although B-V is a good measure of the systematic features of population synthesis models, there is an observed scatter. Fig. 4 shows our model has a greater emission in the red end of the SED than B&C has, this difference is caused by difference in the treatment of the RGB and AGB stages, which affect greatly the red V-I color and almost not at all the blue B-V color.

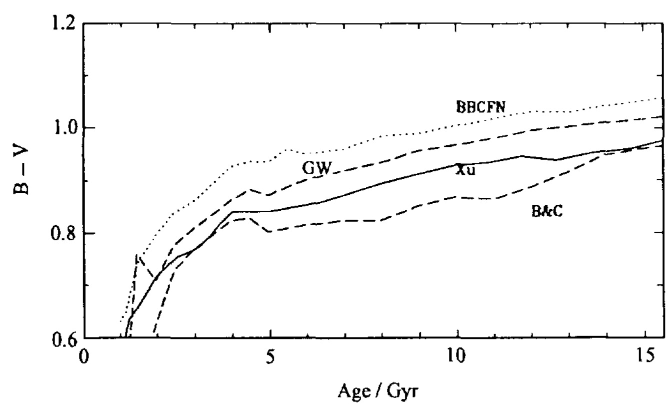

Fig. 3 Evolution of B–V color of an SSP in various models. Our model (denoted by Xu) is systematically redder than Bruzual's but bluer than some others.

The effect of using different forms of IMF is shown in Fig. 5(a), different lower mass cutoffs in 5(b), and different spectral calibrations in 5(c). We have implicitly used Salpeter's IMF (upper cutoff 120 $M_\odot$, lower cutoff 0.07 $M_\odot$, $\alpha = -2.35$). Scalo's IMF[25] and Miller and Scalo's IMF are made up of several power-law segments, and as Fig. 5(a) shows, the effect of different forms is not large, except in the early stage, part of the reason being that the B-V value depends little on low-mass stars, which also accounts for almost the same behavior between 0.2 and 0.1 mass cutoffs in Fig. 5(b). But if the cutoff mass is too high, the color will be bluer and when $M_{\rm low}$ approaches $M_{\rm turnoff}$, the color may turn very red, since the SSP is composed mainly of post main sequence stars. Apart from the degree of freedom of IMF, there is also the degree of freedom of spectral calibration, for the observed dispersion may be considerable. For example, eight stars of different SEDs were all assigned to K3 III[4]. We used their mean values and interpolations to fill the gap in the spectrum. Of course, if we use bluer values we would get a correspondingly bluer curve in Fig. 5(c). Very red colors may also be a consequence of the calibration, for if in constructing the $T_{\rm eff}$ and MK type, we do not distinguish between giants and main sequence stars (in fact we cannot very well isolate the effect of gravity), then the synthetic color can be very red (see Fig. 5(c)).

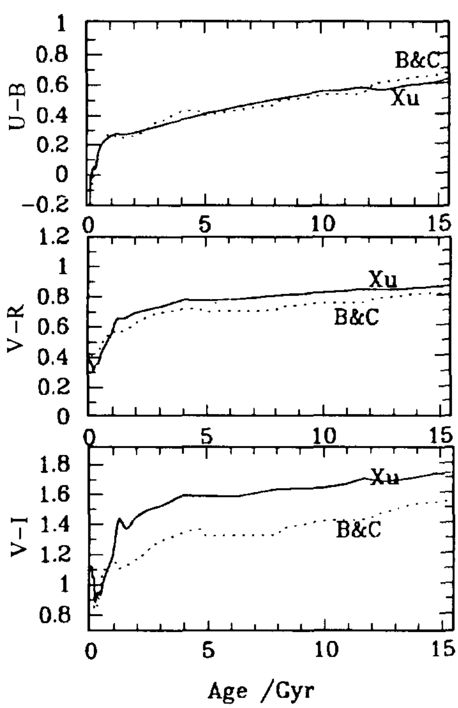

Fig.4 Color evolution of SSP predicted by our and B&C models

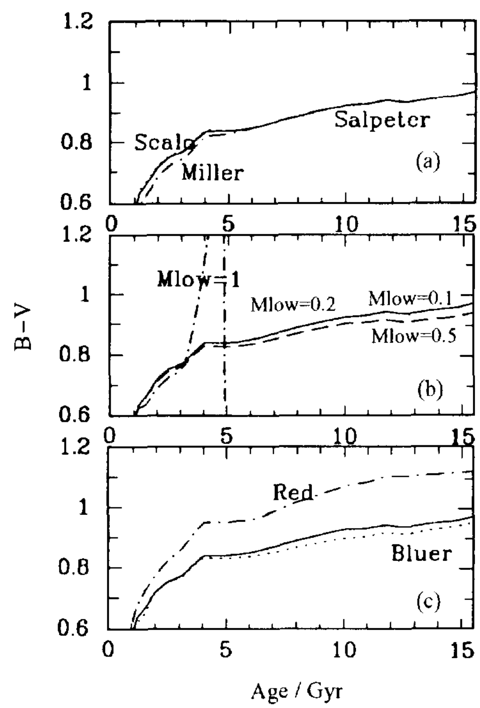

Fig. 5 Influence of input on the predicted B-V evolution of SSP, (a) different forms of IMF, (b) different lower mass cutoffs, (c) different spectral libraries

The transmission curves of the 15 filters of BATC have already been published[14]. We calculated the evolution of SSPs in these 15 bands. Fig. 6 shows that the dimming of the i magnitude can well be represented by a power law, the values shown in the figure have an absolute meaning, for the total mass of the SSP has been normalized to 1 $M_\odot$. When the age exceeds 10^8 yr, a metal-poor SSP is brighter in the i band, for the colors of metal-poor, late-type stars are somewhat bluer, but the power index remains the same.

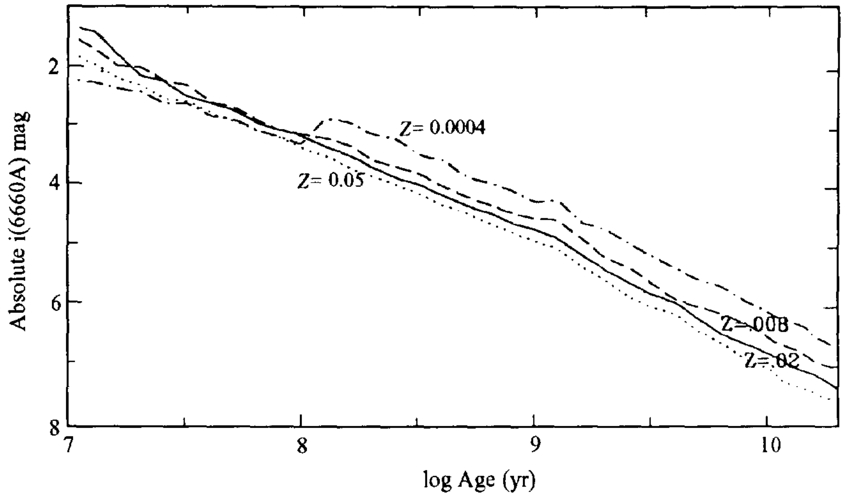

Fig. 6 Evolution of absolute BATC i magnitude of SSPs with different metallicities

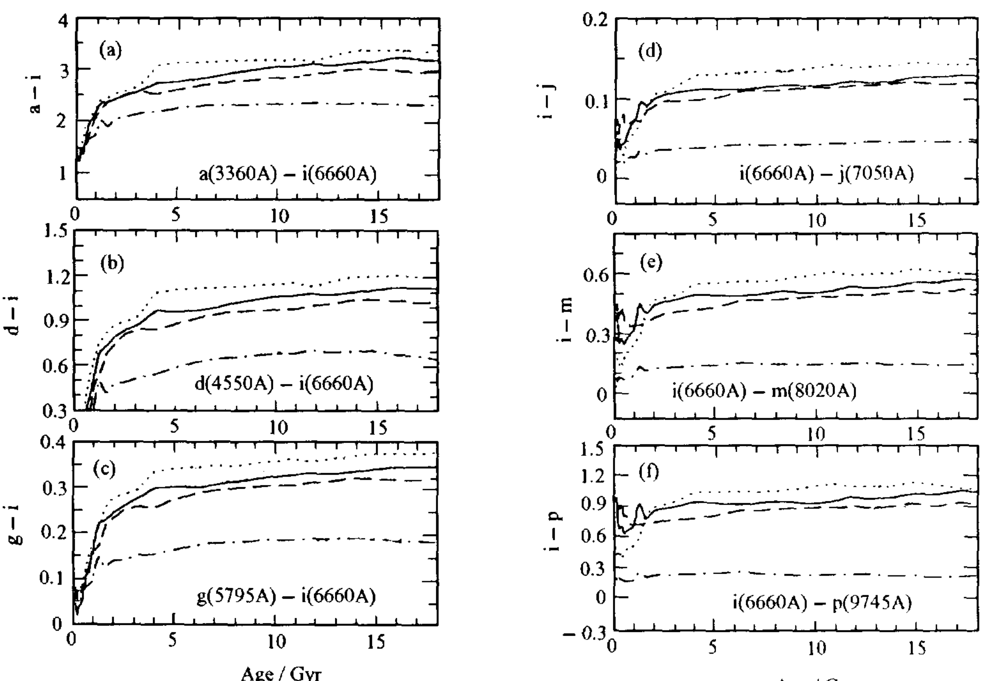

Fig. 7 Evolution of BATC colors of SSPs with different metallicities. Meaning of the curves same as in Fig. 6

Fig. 7 shows the color evolution of SSPs in some of the BATC colors. After the first 3 Gyr (or first 1~2 Gyr for the redder colors), the gradient is consistently slow. The metal-poor SSPs are always bluer and their gradients are smaller still.

Fig. 8 shows, for four SSPs with different metallicities, their SEDs at selected ages. (Arbitrary zero for the vertical scale.) It is clear that the spectrum becomes redder (a) with increasing age and (b) with increasing metallicities. The synthesized spectrum not only reproduces the observed interesting features of starburst populations (the 4000 Å jump, the power-law form), it also agrees well with the observed spectrum of old galaxies (Compare the 10^{10} yr curves with the curve for the giant elliptical galaxy NGC 3379[26]). This means that our model can be used in the discussion of many astrophysical problems, particularly as observed SEDs for a given age and metallicity may not be complete or even available. Also, even if there are spectra of galaxies from spectroscopic observations, they may not be suitable for photometric studies, for it is difficult to measure accurately the continuum in such cases[26].

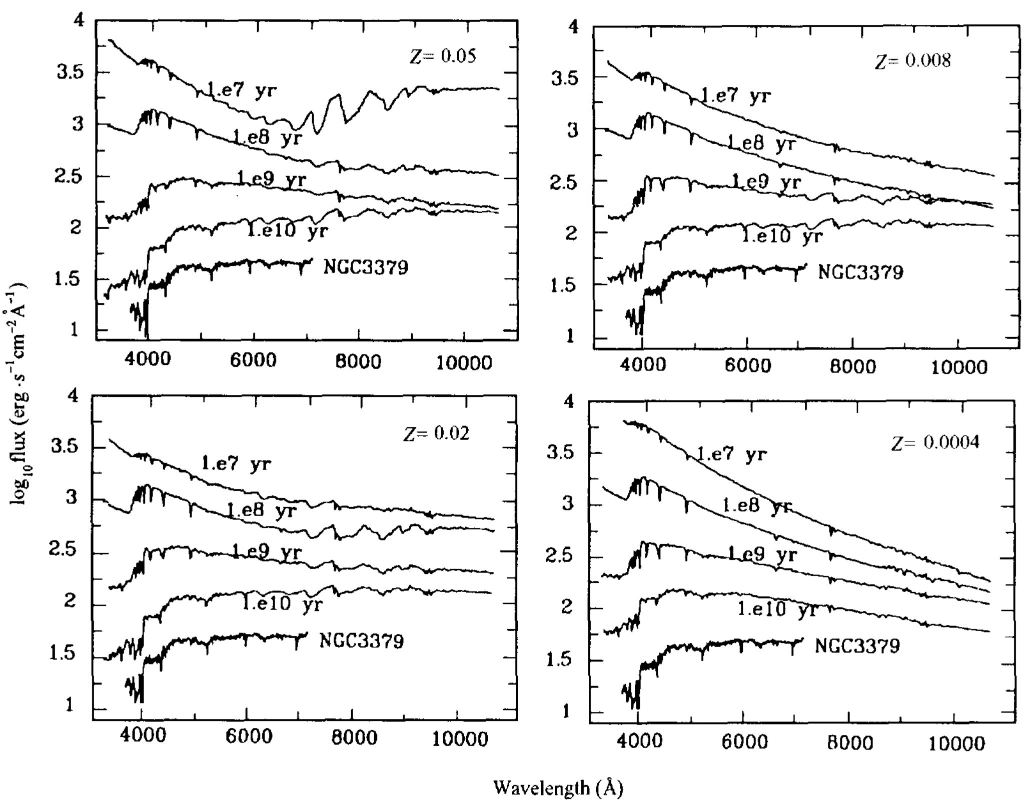

Fig. 8 Synthesized SED at various ages of SSPs of different metallicities. The observed spectrum of the giant elliptical NGC 3379 is added for comparison. Arbitrary normalization of vertical scale

In the SED of the $Z = 0.05$ SSP at age 10^7 yr, there is a bump around 7000 Å. We are still unable to confirm the reality of this peculiar feature (including some large absorption lines), traceable to the spectral calibration used. Late-type (M5 III, M8 III) giants indeed show huge absorption features in their spectra, and when a $Z = 0.05$ star evolves to the position of late-type giants in the H-R diagram, large absorption features will surely appear in the synthesized SED. One point is certain: as the metallicity increases, the SED becomes redder[2,27], and this point is confirmed by the curves of Fig. 8.

4. COLOR EVOLUTION OF GALAXIES

An SSP corresponds to a whole cluster of galaxies. For a single galaxy, we need to consider different star formation rates. Usually, a power-law,

$$\psi(t) = \exp\left(-\frac{t}{\tau}\right) \times \text{const} \tag{1}$$

with $\tau = 0.5$ Gyr–∞ will reproduce the Hubble types from E/S0 to Sd/Irr.

Table 1 lists the UBVRI colors of the synthesized galaxies, together with the observed values[9], for comparison. Our present state of knowledge of the galaxies is such that the observed values either have a large scatter or not available at all. This shows the necessity of a model, which can provide a representative value or fill an observational gap. The data in Table 1 are basically consistent. This shows 1) that the SSP colors predicted by the model are correct (this point is partly made by Fig. 3 above) and 2) that the star formation rate given by (1) represents the physical basis for the Hubble classification. In the comparison we have given a greater weight to B-V, although the model galaxies are somewhat too blue in B-V, and somewhat too red in the other colors.

Table 1 Observed and Synthesized Colors of Galaxies (12 Gyr)

Type	O/S	U–V	B–V	V–R	V–I
E/SO	O	1.41	0.97	0.86	1.63
	S	1.46	0.93	0.84	1.68
Sab	O	0.98	0.79	0.86	···
	S	1.02	0.76	0.75	1.56
Sbc	O	0.63	0.64	0.66	···
	S	0.72	0.62	0.68	1.46
Scd	O	0.41	0.54	0.62	···
	S	0.52	0.52	0.63	1.39
Sdm	O	0.30	0.52	0.53	···
	S	0.34	0.42	0.57	1.30

The luminosity of an SSP is roughly a function of the age and the color is sensitive to the logarithm of the age, so it is difficult to distinguish observationally between old populations. The use of 12 Gyr is simply because the trend of recent determinations of the Hubble constant. Trends shown by photometric observations of galaxies actually hint at a large age for the galaxies[11,12], for otherwise their colors would be too blue. This is essentially the age problem reappearing in the galaxy colors: there is a discrepancy between the theory of stellar evolution and the standard cosmological model.

Table 2 Synthesized BATC Colors of Galaxies (12 Gyr)

Color	E/S0	Sab	Sbc	Scd	Sdm
a–i (3360–6660)	3.10	2.50	2.08	1.82	1.56
b–i (3890–6660)	2.32	1.81	1.45	1.21	0.98
c–i (4210–6660)	1.62	1.28	1.02	0.84	0.65
d–i (4550–6660)	1.08	0.89	0.72	0.60	0.47
e–i (4920–6660)	0.82	0.69	0.57	0.49	0.40
f–i (5270–6660)	0.66	0.56	0.48	0.41	0.34
g–i (5795–6660)	0.33	0.29	0.25	0.22	0.18
h–i (6075–6660)	0.22	0.19	0.16	0.15	0.12
i–j (6660–7050)	0.12	0.11	0.10	0.09	0.09
i–k (6660–7490)	0.40	0.36	0.34	0.32	0.30
i–m (6660–8020)	0.53	0.49	0.46	0.44	0.41
i–n (6660–8480)	0.58	0.54	0.51	0.48	0.45
i–o (6660–9190)	0.87	0.82	0.79	0.77	0.74
i–p (6660–9745)	0.97	0.92	0.89	0.86	0.83

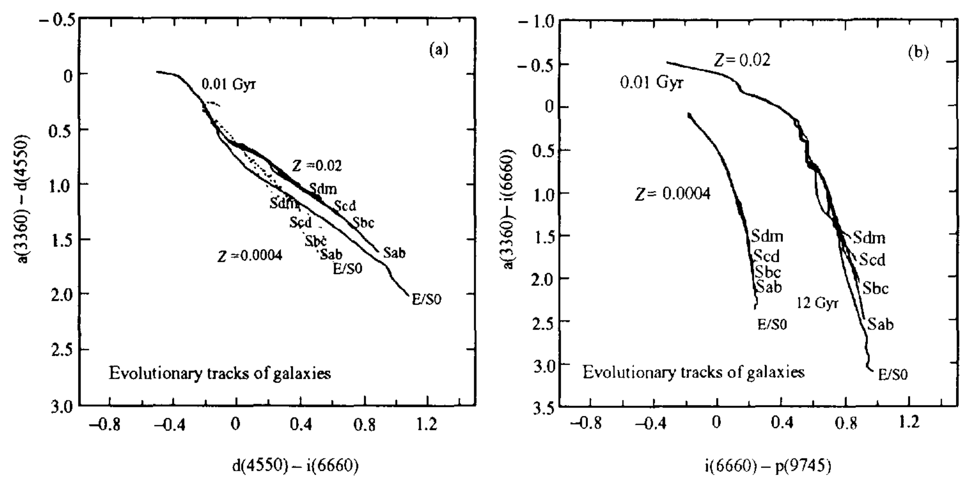

Fig. 9 Evolutionary tracks between 0.001 and 12 Gyr of galaxies of two different metallicities (a) on the blue-blue two-color diagram and (b) the blue-red two-color diagram

The consistency between the UBVRI colors with the observations leads us to expect that there will again be consistency for the 15 BATC colors, shown in Table 2. These data provide a guide for the observations. In principle we can simulate the entire course of evolution of galaxies, but our model did not include internal reddening and light extinction in the Milky Way, nor evolution of chemical elements. Our discussion of different metallicities show that the evolutionary tracks of galaxies of different metallicities are similar in the

BATC blue-blue two-color diagram (Fig. 9(a)), and quite distinct in the blue-red two-color diagram (Fig 9(b)). The age/metallicity degeneracy depends on the wavelength and cannot be subsumed by a simple 3/2 law[2]. Also, different Hubble types can simulate an effect of age, for example, simply from the SED we can hardly differentiate between young E/S0 and old Sdm.

In brief, we have constructed a practical population synthesis model which provides a basis for understanding and guiding the observations. The numerical values predicted by the model are, of course, dependent on the model input, and the reliability of the model goes no further than that.

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