第 15 卷　第 3 期　　天　文　学　进　展　　Vol.15, No.3
1997 年 9 月　　PROGRESS IN ASTRONOMY　　Sep., 1997

星族等时综合模型的现状

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摘　要

总结了星族综合模型的两个要素：处于根本地位的恒星演化计算，以及把理论赫罗图转化为可观测量的光谱定标。

当前恒星模型中的不确定性来自于输入的物理参数：原子数据、对流理论、辐射区的混合和质量丢失。光谱定标不准是因为尚没有准确的温度测定、准确的分光光度测量，而且光谱库中缺少一些类型的恒星。特别是，对 M 型巨星的演化阶段及大气模型，理论上和观测上的知识都很少。

星族综合模型的每个输入参数都有一些持久存在的不确定性。我们比较了关于星族演化的几个模型，讨论了其可靠性及潜在差别的起因。

关 键 词　星系：演化 — 星系：恒星组成 — 恒星：演化

The Status of Isochrone Population Synthesis Models

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(*Recieved 1996 May 14*)

Abstract

We summarize the status of the two main elements of each population synthesis model: the underlying stellar evolution prescription and the spectral calibrations used to transform the theoretical Hertzsprung-Russell diagram into observable.

The uncertainties associated with current stellar models lie in the input physics: atomic data, convection theory, mixing in radiative regions, and mass loss. The spectral calibrations are limited by inaccurate temperature determination, inaccurate spectrophotometry, and by lack of a library including all types of stars. Especially, we seem to be lacking of an understanding of the evolution stages and the atmospheres of M giants for both theory and observation.

国家自然科学基金资助项目

1996 年 5 月 14 日收到

There are persistent ambiguities in virtually every ingredient of population synthesis models. We compare recent models for the spectral evolution of stellar populations. We evaluate the reliability and the origin of potential discrepancies of such models.

Key words galaxies: evolution—galaxies: stellar content—stars: evolution

1 Introduction

Evolution of galaxies can be studied either dynamically or spectrophotometrically. Star formation activities are usually a consequence of dynamical events. As a result, the ongoing star processes have drastic feedback on dynamics. Star formation rate (SFR) in the history of galaxies are usually assigned a simple functional form because of our limited understanding of galactic evolution. Once SFR is prescribed, the luminosity evolution of galaxies for a specified IMF(initial mass function) & specified chemical abundance can be predicted with the aid of population synthesis model. More comprehensive models[5,140] which treat chemical evolution along with luminosity evolution can be constructed essentially in the same spirit. Thus, synthesis models stand at a crucial point where comparisons of theoretical results of evolution models could be made with either photometric or spectral observations.

The concept of stellar populations was invented[7] to analyze external galaxies. Studies in this field have an old history[146], with a traditional ways of trial-and-error to match the best proportions of stars[122,89,53,102,108]. The true physical synthesis model based on stellar evolution began with the development of 'evolutionary population synthesis' (or,'isochrone synthesis') models(e.g. [43], [130], [26], [5], [69], [30], [27], [28], [24], [59], [151], [98], [145], [144], [38]). The technique is based on the property that stellar populations with any star formation history can be expanded in series of instantaneous bursts. In return, differences in the properties predicted for any stellar population can be traced back to differences in the isochrones predicted for instantaneous burst populations with fixed IMFs and metallicities.

The models of Bertelli *et al.*[12] (hereafter BBCFN), Worthey [151] (hereafter GW), and Bruzual & Charlot[27,28] (hereafter B&C) include different updates in the theories of stellar interiors and atmospheres. These models are ideal for analysis of galaxies. The magnitude and color scales of most new models of stellar population synthesis have been tested satisfactorily against observations of star clusters [30,27,24,151,63].

Despite decades of effort, the star formation and chemical evolution history of distant galaxies remain a mystery. One of the problems is that spectral evolution is slow if the youngest stars present are older than about 1 Gyr. Another problem is that both age and metallicity have a similar effect on integrated colors and line strengths. If two stellar populations differ in age and metallicity by dlog *age*/ dlog $Z \sim 3/2$, they will appear virtually identical in all colors and most optical spectral indices[151].

Furthermore, different models also lead to widely different interpretations of galaxy spectra[38]. Such large discrepancies are bound to be caused by differences in the main underlying assumptions, which we conveniently divide into two categories: the stellar evolution theory used to predict the distribution of stars in the theore tical HR diagram and the library of spectra assigned to stars as a function of temperature and luminosity, from which colors are calculated. There appear to be persistent problems in virtually every ingredient of population synthesis models. The most serious problems are the lifetimes and luminosity of stars in post-main sequence evolutionary stages; the temperature of the red giant branch and color-temperature relation for cool stars; and the lack of accurate libraries of stellar spectra, especially for cool stars and for non-solar metallicities. These problems have profound causes. The main one is the high sensitivity of stellar evolution models on the efficiency of several critical factors which are either not sufficiently understood or cannot yet be determined uniquely from comparisons with observations (opacities, heavy element mixture, helium content, convection, diffusion, mass loss, rotational mixing). Other major limitations are the difficult spectral modeling of cool stars and the unavailability of calibration stars for metal-rich populations and populations with altered chemical mixes.

In the following we make summaries on the two elements of synthesis model. For further detail, we recommand the recent admirable review ([38]). We emphasize that synthesis model calculations provide essential guidance, rather than a predictable precise analysis.

2 Stellar Libraries

2.1 The general underlying physics

There are several fundamental sources of limitation in current stellar models: atomic data (i.e., radiative opacities, heavy element mixture, helium content, reaction rates), convection theory (i.e., mixing length, overshoot*, semiconvection), mixing in radiative regions (i.e., rotational mixing, thermal diffusion, gravitational settling), and mass loss(see, e.g., [39]).

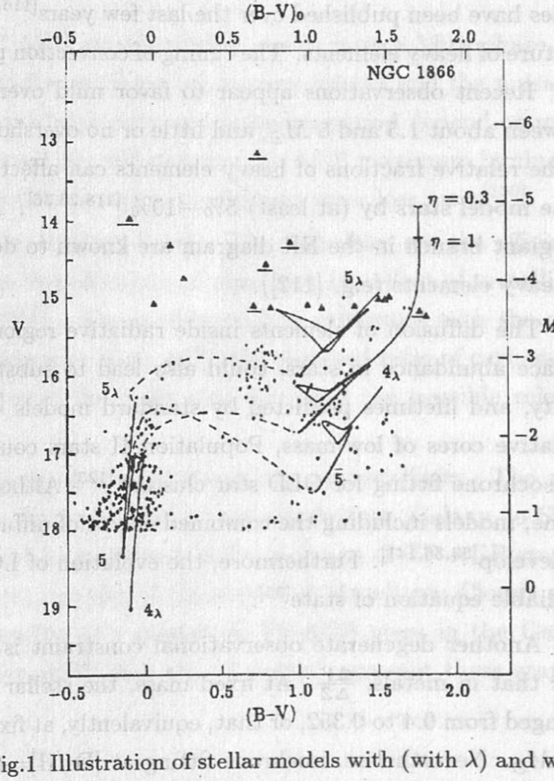

Fig.1 Illustration of stellar models with (with λ) and without convective overshooting when compared with observation. The number $\eta = 0.3$, 1 visualize the maximum AGB lumminosity in occurrence of mass loss[11].

* 'Convective overshooting' refers to the increase of the convective zone when its boundary is defined where the velocities(instead of accelerations) of convective elements vanish.

Figure 1 shows an example of the role of convective overshooting and stellar wind on the evolution of intermediate mass stars. The dots and triangles are photometric data of stars of NGC 1866, a young globular cluster in Large Magellanic Cloud. Its age was estimated about 8.6×10^7 yr and with a turnoff mass about $5M_\odot$ and a composition of $Y = 0.273$ and $Z = 0.016$. One of the troubles for previous standard models is the overprediction of the number of stars in post-main sequence stars. The λ models in Fig.1(the $5_\lambda M_\odot$ and $4_\lambda M_\odot$) stand for overshooting with $\lambda = 1$. The adopted value of λ can influence the fitted age from giant branch fitting. The extension of AGB luminosity is also an indicator of age. To be compatible with other age indicators, more mass has to be lost during the ascent of the AGB or in the nebula ejection than previously thought. If mass loss is predicted by Reimers'(1975)[155] empirical relationship, $\eta = 1$ is about correct in this case (However, even if above values are taken into account, models still have difficulty in explaining those superluminous stars(triangles) as in AGB phase.).

Stellar models are sensitive to changes in radiative opacities [118,23,35,36]. Several opacity tables have been published over the last few years[116,79,78,120,2] including different choices for the mixture of heavy elements. The tuning of convection parameters depends on the adopted opacities [23]. Recent observations appear to favor mild overshooting in the cores of stars with masses between about 1.5 and 5 $M_\odot$, and little or no overshooting in lower-mass stars[23,100,48]. Changes in the relative fractions of heavy elements can affect the lifetime, temperature, or luminosity of some model stars by (at least) 5%—10% [118,23,36]. The morphologies of the turn off and of the red giant branch in the HR diagram are known to depend sensitively on the relative abundance of heavy elements (e.g. [112]).

The diffusion of elements inside radiative regions, which has long been invoked to explain surface abundance in stars, could also lead to substantial revisions of the temperatures, luminosity, and lifetimes predicted by standard models [46,114,34]. Including helium diffusion in the radiative cores of low-mass, Population II stars could reduce by 15% to 25% the ages derived by isochrone fitting for OLD star clusters.[125] Although the helium diffusion may not be so extreme, models including the combined effects of diffusion and rotational mixing are only starting to develop[33,36,141]. Furthermore, the evolution of LOW-MASS stars still suffer from the lack of a reliable equation of state[35].

Another degenerate observational constraint is the ratio of (initial) enrichment in helium over that in metals, $\frac{\Delta Y}{\Delta Z}$. At fixed mass, the stellar lifetimes increase by up to 40% when Y is changed from 0.4 to 0.352, or that, equivalently, at fixed age the turnoff mass increases by roughly 0.1 $M_\odot$. Nevertheless, isochrone fitting at [Fe/H]=+0.5 reports modulation of only 15% in the inferred age if $\frac{\Delta Y}{\Delta Z}$ is set to 0.0[151] instead of 2.7 (the observation allowed range is 2–7[111,104]). Such insensitivity is due to the fact that the increase in turnoff mass when Y decreases is also balanced by a drop in luminosity and temperature.

2.2 The advanced stages

The advanced stages suffer from uncertainties: mass loss on the red giant branch, the treatment of convection during core-helium burning and thermal pulses of AGB stars.

The relative numbers of RGB, HB, and AGB stars in 15 metal-poor globular clusters in the Milky Way halo[112] require that the amount of helium burnt in the cores of stars on the horizontal branch be larger than the amount available at the RGB tip. The most natural candidates for helium refuel are semiconvection (an actual theoretical prediction) and overshooting. A characteristic instability near core-helium exhaustion, referred to as 'breathing convection', can also lengthen the core-helium burning lifetime[31]. But it may be an artifact of simple algorithm[23]. The new Geneva tracks (favorites of the B&C model) include breathing convection but neither semiconvection nor overshooting are being tested against observations[36].

For low and intermediate-mass stars, AGB phase is characterized by periodic thermal pulses of the He-shell and by heavy, but probably episodic mass loss[153]. Stars then build up a circumstellar shell that is crucial for the synthesized infrared light. TP- AGB stars are also important for the ultraviolet light of old stellar populations because of the final core mass at envelope ejection.

Both observational[27,73] and theoretical[12] approaches have been adopted to include TP-AGB stars in population synthesis models.

Infrared Observations suggest that TP-AGB stars probably evolve from a Mira phase into a strong OH-maser emission phase, in which the envelope has become thicker and the pulsation period become longer (e.g. [8]). The particular luminosity and pulsation period depend on main-sequence progenitor mass [71]. Planned infrared sky will measure the AGB maximum luminosity and number ratios of stars of different compositions and with different mass loss rates[150].

Theoretical models[71] of TP-AGB stars develops slowly. The difficulties are the efficiency of carbon dredge up, the driving mechanism and efficiency of mass loss, the effect of metallicity, and the parameters of convection[113,21,18,140,68]. The models may be calibrated with the core-mass luminosity relation[105], the period-luminosity relation[76], the observed ratio of carbon-rich to oxygen-rich stars, observational estimates of the mass loss rate, and the possible relation between period and mass loss rate [140,71].

Some properties of TP-AGB stars appear to depend sensitively on metallicity. The ratio of carbon-rich to oxygen-rich stars changes for four order of magnitude from Galaxy to Small Magellanic Cloud [17]. So, uncertainties would be persistent in the inclusion of TP-AGB stars in population synthesis models even after larger samples of Galactic and Magellanic Clouds stars become available. Nonetheless, infrared spectra of a sample of TP-AGB stars in the Galaxy and Large Magellanic Cloud are being observed[88] that should better represent these stars in population synthesis models.

2.3 The massive stars

Other uncertainties associated with massive stars($> 2M_{\odot}$) include the photoionizing radiation and energy output, the relative numbers of red and blue supergiants, the evolution of Wolf-Rayet stars, and the rate of Supernova II[62]. Current models[32,61,92] lack the coupling of the interior physics with that of the outer atmosphere. The strength of the stellar wind is usually parameterized in a simple way and roughly calibrated against available observations[96,39]. The evolution of stars with 10 $M_{\odot}$ and 30 $M_{\odot}$ is extremely sensitive to the details of internal mixing and affects the relative ratio of red to blue supergiants; mass-loss is essentially important to more massive stars which depletes their progeny (the so-called hypergiants) to appear as bare He nuclei(WR stars). These effects depend sensitively on the abundance of heavy elements[96].

2.4 The Hot Star Problem For Old Populations

A significant extreme UV(shortward of 2000Å) flux is present for old populations[13,49], which is most likely produced by a combination of (1) very hot post-AGB stars on their way to become white dwarfs (The resolved post-AGB stars could account for about 20% to 50% of the total ultraviolet flux[13]), (2) a category of 'extreme blue horizontal branch' (EHB) stars, and (3) binaries[110]. The causes[38] of EHB could be of very low metallicity; old and of excessive lose of mass during RGB(red giant branch) phase; or old and very high metallicity.

2.5 Binarism

An expected consequence of binaries is to give rise (by coalescence) to 'blue stragglers'. Binaries also produce Type Ia supernovae, and hence it is an important factor in the chemical enrichment of galaxies. The Yale Bright Star Catalog shows a binary frequency of over 50%[52].

2.6 stellar libraries

There are three different stellar evolution calculations most widely used in population synthesis models: the VandenBerg(Yale), Geneva, and Padova libraries.The models are all normalized to the Sun at 4.6 Gyr.

Geneva set[118] traces till white-dwarf cooling(or supernova explosion for $m > 8\ M_\odot$). It is based on the computations by [118] for $m > 2M_\odot$, [36] for $0.9 < m < 2\ M_\odot$, and [24] for $0.6 < m < 0.8\ M_\odot$. They were supplemented with a semi-empirical prescription for TP-AGB, with post-AGB evolutionary tracks, and with unevolving main-sequence stars in the mass range $0.1 < m < 0.6\ M_\odot$ [38]. The Geneva tracks include mild overshooting in the convective cores of stars more massive than 1.5 $M_\odot$. The abundance are $X = 0.68$, $Y = 0.30$, and $Z = 0.02$, and include new opacities.

The Padova stellar isochrones[4,23,54,55,56] encompasses a wide range of initial chemical compositions, from $Z = 0.0004$ to $Z = 0.1$ with $Y = 2.5Z + 0.23(Z_\odot = 0.02$ and $Y_\odot = 0.28)$ assumed. The tracks use new radiative opacities and include all phases of stellar evolution. The amount of overshooting in the convective cores of stars more massive than $1.5M_\odot$ is similar to Geneva tracks. Overshooting is also included, with a reduced efficiency, in the cores of stars with masses between 1.0 $M_\odot$ and 1.5 $M_\odot$. The tracks include efficient overshooting in the convective envelopes of low-and intermediate-mass stars as suggested by [3]. This homogeneous set of tracks were supplemented with a prescription for TP-AGB and with post-AGB evolutionary tracks.

Models of classical theory of convection (no overshooting) and of classical opacities[77] are still favored by some people[151]. Yale isochrones[136–138,67] extend from the middle main sequence to the tip of the RGB, and the various chemical compositions range from $Z = 0.0001$ to $Z = 0.1$ with explicit Y-dependence $Y = 2.7Z + 0.228(Z_\odot = 0.0169$ and $Y_\odot = 0.274)$ assumed. These isochrones are extended down the lower main sequence using tracks of [135]. HB phase was approximated by a single red clump, and AGB regime was followed by a compilation of theoretical prescription.

Yale tracks are applied to stars with ages between 1.5 and 18 Gyr.

3 Spectral Calibrations

The starlight we see comes from the photosphere of a star. It reflects combined effects of temperature, pressure, turbulence, and chemical compositions. To convert stellar tracks into observable (for purpose of population synthesis, or, more elementarily for comparison of stellar tracks in HR diagrams), we need to establish a library of spectral calibrations to relate various kinds of stellar spectral energy distributions(SEDs) with different physical parameters. This can proceed either through theoretical modeling of stellar atmospheres or by empirical calibration of observed stellar spectra.

3.1 Models of stellar atmospheres

For the modeling of stellar atmospheres[15,83,84,101], the emitted spectrum deviates from that of a black body because of continuous opacity (absorption) and line opacity happening in this outer region. The problems assosiated with line opacity stem from the very large number of lines that can arise and the need to know their identification and atomic parameters. Data for millions of lines have been compiled for this purpose[83]. Although line opacity is not strictly a part of the continuous opacity, the cumulative effect of many lines can behave much like continuous opacity in the upper photosphere. This may be rather important in some cases[83]. The spectra of M giants (i.e., with $T_{\rm eff} < 3900$ K) are also difficult to model theoretically because these are blanketed mostly by molecular opacity and because their atmospheres tend to be extremely extended. This is unfortunate for the purpose of population synthesis modeling because M giants dominate the light at wavelengths redward of about 1 micron for metal-rich populations of most ages. Our understanding in this area can progress by studies of Galactic, Magellanic, and Bulge M giants; the inclusion of always more realistic opacities due to water and other important molecules; a more complete determination of the color-temperature scale; and models of atmospheric structure in M giants to get reliable pressure boundary conditions for evolutionary calculations. Stellar populations of different metallicities, and even different elemental mixes, may then be eventually modeled with confidence, but this seems a long way ahead. There are also problems in the model atmospheres for massive stars (i.e., LTE(local thermal equilibrium)) or non-LTE, static or expanding envelopes, etc.[83,84,40,119].

The temperature scale as a function of V–K color for giant, solar-metallicity stars of Kurucz models in the range $3250 < T_{\rm eff} < 5000$ K was in good agreement with Ridgway except around $T_{\rm eff} \sim 3500$ K, where the models appear to be about 0.5 mag bluer. Furthermore[107], in warm giants (around 5000 K) the predicted B–V color based on Kurucz model fluxes was found to be systematically redder by about 0.06 mag than Johnson's[81]. Recent calibration[44,93] of the optical/infrared colors and temperature and metallicity scales of model atmospheres conclude systematic deviations. The sample stars so far mainly cover the metallicityrange $-2.5 < [M/H] < 0.0$.

3.2 Empirical compilation

For an empirically collected spectral library, we need to calibrate its effective temperature, luminosity class (surface gravity), and bolometric correction so that theoretical track scan be made to be connected to observable. The spectral(steller atmospheric) MK classification scheme cannot be unambiguously transferred into other schemes based on broad band colors or schemes based on physical stellar quantities such as effective temperature (outmost stellar interior). However we are in the hope that the same physics underlies these classification schemes so that spectral calibration can make sense.

The most commonly used color-temperature scale for solar-metallicity G8 to M6 giants is what is derived by Ridgway *et al.*[115], which relates the V-K color with $T_{\rm eff}$. Other modern methods based on model atmosphere analysis or the method of total-to-infrared flux ratio give the similar results, usually with a discrepancy less than 50 K[131,132,16,10]. The V-K color presents itself as a nearly optimum color for temperature estimates in cool stars for two main reasons. First, the range of V-K colors is large over the range of cool star temperatures, which minimizes the uncertainty caused by observational errors. Second, no study based on model atmospheres has so far indicated any significant dependence of the V-K color on metallicity for temperatures in the range $4000 < T_{\rm eff} < 50000$ K, hence making the V-K color useful to calibrate non-solar metallicity stars as well. This insensitivity may be problematic for cooler stars[14] and for very metal poor stars[10].

Effective temperature is particularly useful in a few situations, for example, in connecting atmosphere to interior models. Those involving broad wavelength coverage are susceptible to the

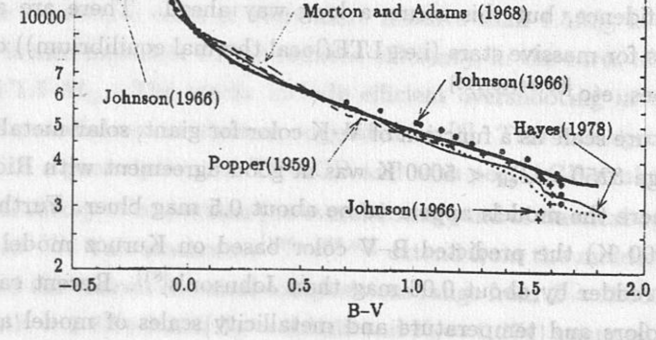

Fig.2 Some of the temperature calibrations published over the years are compared[65].

complications of interstellar reddening. Some of the temparature-sensitive spectral features can also be gravity-dependent. The topics of stellar radii and temperatures are closely related.

Over the years numerous temperature calibrations have been published (Fig.2). Many of these are based on relatively few stars, and each was subject to change as absolute calibrations improved, as better and more complete bolometric corrections were measured, and as more numerous and precise angular diameters became available. Older calibrations were slightly cooler for both early and late type stars for $T_{\rm eff}$–B–V data[10,42,72,48,91,65]. The hottest stars are from [133],[85],[65]. Other calibration methods include [45],[123],[20], etc. The Metallicity effects in determining $T_{\rm eff}$ are investigated by [6],[50] (extreme helium); [60] (metal poor); [117] (Carbon). $T_{\rm eff}$ of white dwarfs[74], Wolf-Rayet stars[134] are also determined. There are generalized spectral-method to determine temperatures [65,154].

The luminosity class of MK classification corresponds to surface gravity, which controls the scale of the pressure distributions. In addition to gas pressure, contributions to the hydrostatic support may come from radiation pressure, magnetic fields, and velocity fields. Any g value obtained by the usual analysis of a stellar spectrum is the EFFECTIVE(corresponds to pressure contribution) gravity needed in hydrostatic equation. In extreme cases, it may differ from $\frac{GM}{R^2}$ because of these other pressures. The measure of photospheric pressure is from: (1) Continuum as a pressure indicator(Balmer discontinuity D, or UB) [86]; (2)Pressure sensitivity in the hydrogen lines[9]; (3)Other strong lines[51]; (4)The weaker lines[95]; (5)The helium abundance (The role of helium in shaping stellar spectra is in many respects equivalent to that of gravity); (6) Binaries[139].

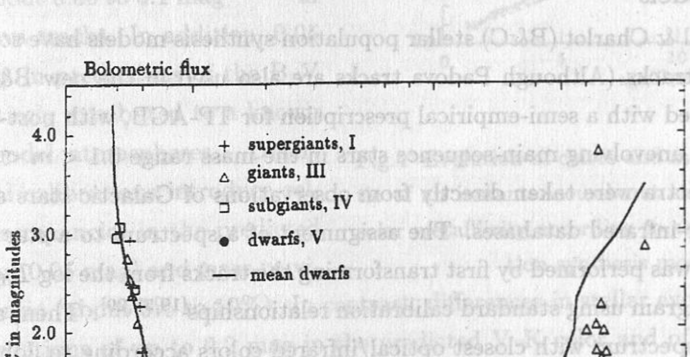

Fig.3 B.C. as determined by various observations[65].

Bolometric correction (B.C.) (cf Fig.3) is collected in [42] (for stars hotter than the Sun), [72] (for mean dwarfs & giants), and [107] (for giants).

Sources of spectra suitable for synthesis purpose are enumerated in Table 1. The optical stellar library can be extrapolated to ultraviolet from the IUE databases and the near-infrared obseravation[106,58]. Spectra of unblanketed blackbody(or sometimes model atmospheres[83]) can be attached at the extreme ends, or for extreme hot stars($T_{\rm eff} > 50000$K).

The spectra of M giants are particularly important. In spite of of the effort [90] to build an observational library encompassing a few hundred optical/infrared spectra of stars with metallicities in the range $-2.0 < [\frac{\rm Fe}{\rm H}] < +0.5$.), the uncertainty in calibrated V–K color is 2 mag and uncertainty in B.C. is 1 mag. Thus many authors make adjustment on the spectral calibration to match the observation [24,64].

The main reason for the absence of a reliable color- temperature scale at such cool temperatures is the scarcity of normal (non-Mira) giant stars of spectral types M7 and M8 in the solar neighborhood. The other absent template stars include metal-rich stars of any age, and stars of solar or greater metallicity but with enhanced abundance of light elements similar to those found in the Galactic Bulge and external galaxies. It is important to build a library of all stars because metal abundance of stellar atmosphere not only have galactic variations, but also evolutionary changes.

4 Application of Population Synthesis Models

4.1 Latest models

The Bruzual & Charlot (B&C) stellar population synthesis models have solar metallicity and include Geneva tracks (Although Padova tracks are also used in the new B&C models). They were supplemented with a semi-empirical prescription for TP-AGB, with post-AGB evolutionary tracks, and with unevolving main-sequence stars in the mass range $0.1 < m < 0.6\ M_\odot$ [37]. Most of the stellar spectra were taken directly from observations of Galactic stars at near-ultraviolet, optical, and near-infrared databases. The assignment of a spectrum to a star at any position in the HR diagram was performed by first transforming the tracks from the log $T_{\rm eff}$–log L diagram to the (V, B–V) diagram using standard calibration relationships[19,57,29]. Then, a star was assigned to the available spectrum with closest optical/infrared colors according to Johnson's (1961) calibration of the UBVRIJKL photometric system as a function of B–V color and luminosity class. For giant stars cooler than about 5000 K, the V–K[115] color-temperature scale was used. The spectra of TP-AGB stars were calibrated separately using the colors of Mira Ceti and IK Tau[37].

The Padova isochrones constitute the basis of BBCFN [24] population synthesis models and recent improvements[25,126,144]. Model atmosphere was used[14,83,86]. The spectra of cooler stars were constructed from a composite of three catalogs of observational spectra of Galactic disk and bulge stars[124,129,87]. For cool giants, BBCFN first calibrated the observational spectra using a combination of the color-temperature scales of [115] and [87]. They include a revision of spectral calibration by matching the observed BVR I color-magnitude diagram of the metal rich globular cluster NGC 655.

The GW(G. Worthey) model uses Yale tracks. The evolution beyond the tip of the RGB was approximated by a single red clump for the core-helium burning phase, and, by isochrones inferred from various theoretical prescriptions through the early AGB up to the thermally-pulsing regime at the end of the AGB. Stars hotter than 3750 K were again approximated by model atmospheres[84]. For cooler stars, composite spectra were assembled by patching together model atmospheres[15] and optical observational spectra of M giants[70].

4.2 Reliability

The main uncertainties in modern population synthesis models appear to originate from the underlying stellar evolution theory, the color-temperature scale of giant stars, and, for non-solar abundance in particular, the flux libraries.

The predicted color is similar in the GW and BBCFN models (cf Fig.4). It is 0.04 to 0.07 mag bluer in B–V in the B&C model computed with either the Geneva or Padua tracks. The various models differ more markedly(∼ 0.3 mag) in V–K color[38]. The Padova tracks causes a redder synthesized color by about 0.05 to 0.1 mag [27,28] in B–V than Geneva tracks. In addition, 0.05 mag discrepancy in predictions of the B–V color can be entirely attributed to a known limitation of model atmospheres. Differences in spectral calibrations introduce relatively small discrepancies in the predicted V–K color (about 0.05 mag) and mass-to-visual light ratio (about 5% to 10%). In contrast, differences in stellar evolution prescriptions can produce deviations of up to 0.2 mag in the predicted V–K color and of 15% to 20% in the predicted mass-to-visual light ratio[38]. For spectral indices it was approximately 25% at old ages (> 10 Gyr), i.e., similar to the uncertainty obtained by using the B–V color for dust-free galaxies.

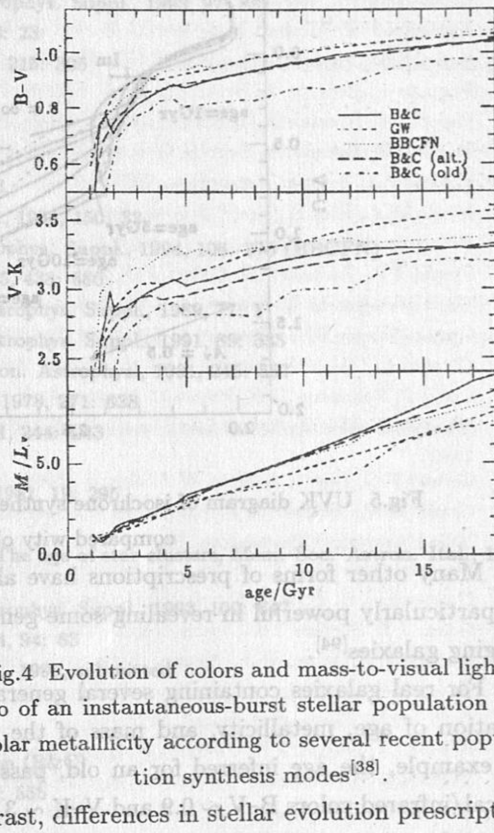

Fig.4 Evolution of colors and mass-to-visual light ratio of an instantaneous-burst stellar population wity solar metalllicity according to several recent population synthesis modes[38].

4.3 Applied to galaxies

The results of synthesis can be directed compared to the integrated light of clusters. Besides, galaxies of different Hubble types seem to have different star formation histories. In Fig.5, we show that a simple exponential prescription of star formation laws:

$$\Psi(t) = \exp(-t/\tau) * \text{const.} \tag{1}$$

with $\tau = 0.5 - \infty$ Gyr can reproduce many photometric properties of galaxies from E/S0 to Sd/Irr. In the figure, evolutionary tracks with time scales $\tau = 0.5, 1, 2, 3, 6, 9$ are shown. The mean observed colors of bright galaxies of various Hubble types are indicated with their dispersions. The dotted thin lines are the loci at fixed ages(1,5,10,and 15Gyr). The arrow is the reddening vector.

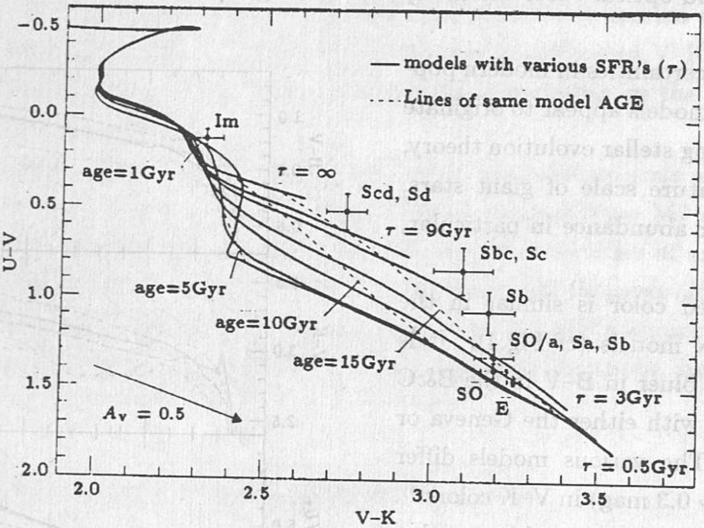

Fig.5 UVK diagram of isochrone synthesis models convolved with decaying SFRs compared wity observed galaxis[37]

Many other forms of prescriptions have also been tried and tested. The synthesis models are particularly powerful in revealing some general properties of burst population happening in merging galaxies[94].

For real galaxies containing several generations of stars with different metallicities, determination of age, metallicity, and mass of the various components will be far more uncertain. For example, the age inferred for an old, passively evolving galaxy with solar metallicity and optical/infrared colors B–V ~ 0.9 and V–K ~ 3.3 can range from roughly 4 to 13 Gyr[151]. In addition, the presence of dust in real galaxies can complicate the determination because the effects of dust on broad-band colors are almost undistinguishable from those of age and metallicity.

Although spectral indices seem to provide a way to partially isolate the degeneracy, caution must be paid in deriving galaxy ages from integrated narrow indices because of the great sensitivity of some indices to the last episode of star formation alone[151].

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