SYNTHETIC INTEGRATED SPECTRAL PROPERTIES OF THE OLD GALACTIC OPEN CLUSTERS ARE STUDIED IN THIS WORK, IN WHICH 27 GALACTIC OPEN CLUSTERS OF AGES $\geq 1$ Gyr ARE SELECTED AS THE WORKING SAMPLE. BASED ON THE PHOTOMETRIC OBSERVATIONS OF THESE OPEN CLUSTERS, A SYNTHETIC INTEGRATED SPECTRUM HAS BEEN MADE FOR THE STELLAR POPULATION OF EACH CLUSTER. THE EFFECTS OF BLUE STRAGGLER (BS) STARS ON THE CONVENTIONAL SIMPLE STELLAR POPULATION (SSP) MODEL ARE ANALYZED ON AN INDIVIDUAL CLUSTER BASIS. IT IS SHOWN THAT THE BSs, WHOSE POSITIONS IN THE COLOR-MAGNITUDE DIAGRAMS CANNOT BE PREDICTED BY THE CURRENT SINGLE-STAR EVOLUTION THEORY, REQUIRE SIGNIFICANT MODIFICATIONS TO THE INTEGRATED PROPERTIES OF THE THEORETICAL SSP MODEL. THE SYNTHESIZED INTEGRATED SPECTRAL ENERGY DISTRIBUTIONS (ISEDs) OF OUR SAMPLE CLUSTERS ARE DRAMATICALLY DIFFERENT FROM THOSE OF SSPs BASED ON AN ISOCORNE ONLY. THE BS-CORRECTED ISEDs OF STELLAR POPULATIONS SHOW SYSTEMATIC ENHANCEMENTS TOWARD SHORTER WAVELENGTHS IN THE SPECTRA. WHEN MEASURED WITH BROADBAND COLORS IN UNRESOLVABLE CONDITIONS, THE AGE OF A STELLAR POPULATION CAN BE SERIOUSLY UNDERESTIMATED BY THE CONVENTIONAL SSP MODEL. THEREFORE, CONSIDERING THE COMMON EXISTENCE OF BS COMPONENTS IN REAL STELLAR POPULATIONS, WE SHOULD EXPECT CONSIDERABLE ALTERATIONS OF THE CONVENTIONAL ISEDs WHEN WE APPLY THE TECHNIQUE OF EVOLUTIONARY POPULATION SYNTHESIS TO MORE COMPLICATED STELLAR SYSTEMS.

SUBJECT HEADINGS: GALAXIES: STELLAR CONTENT — GALAXY: STELLAR CONTENT — OPEN CLUSTERS AND ASSOCIATIONS: GENERAL

1. INTRODUCTION

Over many years of substantial practice, evolutionary population synthesis (EPS) has proved to be a powerful tool for the study of the evolution of stellar systems. Its use is based on its great success in the understanding of stars, including stellar structure and evolution (without taking into account rotation, magnetic field, and binarity) and the properties of stellar radiation from their atmospheres. As the basic building blocks of synthetic spectra of galaxies, simple stellar populations (SSPs) are built by integrating the library of isochrones based on theoretical evolutionary tracks, the library of stellar spectrum of individual stars, and the stellar initial mass function (IMF). The first two ingredients are given at a certain chemical composition, while the IMF is usually considered to be universal (see Bressan et al. 1994 for a review).

As a solid basis for studying complex stellar systems, the EPS method is very successful in many respects. In analyzing the stellar populations of composite systems such as galaxies, EPS reproduces the overall spectral properties of the stellar components and also derives the star formation and chemical evolution histories (Schulz et al. 2002). In the case of simple stellar systems like star clusters, relying on almost perfect isochrone fitting to the photometric observations of the systems, the conventional SSP model can give fairly good interpretations of most of the evolutionary features of star clusters, i.e., the main sequence (MS), red giant branch (RGB), horizontal branch (HB), and red clump giants, using the integrated light of these components. However, exceptions do exist. It is often observed that a certain number of definite member stars hold positions in the color-magnitude diagrams (CMDs) that cannot be predicted by single-star evolution theory, and consequently the integrated contributions of these stragglers to the total radiation are ignored by the conventional SSP model. Most of the unresolved objects are related to a binary scenario and stellar collisional events, such as blue straggler (BS) stars in stellar systems. In the case of open clusters, BSs, being the most luminous blue objects, present a major challenge to the SSP model (Deng et al. 1999; Schiavon et al. 2004).

Since the first identification by Sandage (1953) in the cluster M3, BSs have been observed in almost all star clusters and dwarf galaxies, and they presumably exist in all other stellar systems (Stryker 1993). These enigmatic stars are located to the bluer and brighter side of the cluster turnoff region in a CMD and appear to be straggling away from the regular evolutionary path; hence the name “blue stragglers.” As for the nature of these objects, observations suggest that BSs are more massive than the regular stars in the turnoff region, and thus they are most likely remnants of stellar merger events or still-binary systems with luminous blue components.

The primary ways in which BSs are formed are the dynamical evolution of close binaries and collisions in the high-density areas in clusters. (Ferraro et al. 1997, 2003; Piotto et al. 1999). As suggested by mounting evidence, if BSs are partially the result of mass transfer or coalescence during resonant interactions involving binary systems (Leonard 1989; Bacon et al. 1996), they would be visible tracers of binary populations and in addition provide an opportunity for learning how interactions in binary systems affect stellar evolution (Pols & Marinus 1994). Meanwhile, an appreciable frequency of single-single star collisions generally occurs only in the cores of the densest clusters (Hills & Day 1976), where BSs can provide observational constraints on stellar collision cross sections for tidal captures, direct collisions, and corresponding productions in dense stellar environments (Bailyn 1995; Lombardi et al. 2002). Regardless of the origins of BSs, when mergers occur, many of the cluster properties are affected. The remarkable central concentration of BSs provides an effective way to examine various aspects of cluster dynamics, such as two-body relaxation in binary systems, core collapse rates, mass segregation and depletion of low-mass stars in stellar systems, and energy equipartition among the cluster member stars. Moreover, BSs exist in significant
numbers in both young and old populations. They provide a component that is remarkably hotter than the rest of the cluster (Manteiga et al. 1989) and raise the possibility of bluer integrated colors and integrated spectral energy distributions (ISEDs; Deng et al. 1999). Therefore, population syntheses definitely must account for the presence of numerous BSs in star clusters, and possibly in dwarf ellipsoids, ellipticals, and other galaxies as well. It is important to gather empirical information on BSs in order to characterize correctly the overall properties of populations in stellar systems according to integrated light studies.

Based on the assumption that all members are born simultaneously and therefore have the same age and metallicity, open and globular clusters are considered to be the best SSP templates in the real world (Bica & Alloin 1986; Battinelli et al. 1994). In this paper, our attention is on the BSs in Galactic open clusters. The reason for this is that, for the chemical composition range covered by Galactic Population I clusters, BSs are the most luminous blue objects and their contributions to the integrated light are the most prominent; this is especially marked for old open clusters when the red clump instead of blue HB is populated. The BS effects on the ISEDs become far less important for the Galactic globular clusters, where the most luminous blue objects are the HB stars.

Since direct observation of cluster integrated light (Bica & Alloin 1986) cannot address the problems of field contamination and gravitational evaporation of low-mass stars, it is not possible to get the proper ISED of a cluster in that way. Pure theoretical efforts based on the current theory of stellar evolution also fail at this point simply because of the stragglers. Keeping these facts in mind, we proposed a semiempirical approach of building cluster ISED in our previous work (Deng et al. 1999): after careful membership analysis, the general stellar ingredients well fitted by a theoretical isochrone are represented by the conventional SSP model, in which the “missing” low-mass stars can be recovered with proper initial mass function, so that the true meaning of the SSP is conserved; all the stragglers are included in the ISED by derivation of the spectra from observations.

The importance of BSs for studies of stellar formation and evolution and for population analysis of galaxies has been stressed by numerous work (see Stryker 1993 for a review). What we show in this paper, by using old Galactic open clusters, are the effects of BSs on the integrated light of a stellar system and on the theoretical SSP model. With a sample of 27 Galactic open clusters of ages \( \geq 1 \) Gyr, we present in this work a set of integrated spectra and modified integrated \( B - V \) color of the clusters. Comparison between the conventional approach and our results is made, aimed at investigating the BS contribution to the conventional SSP model. A short report of our working sample is given in the next section. In § 3 population synthesis is performed for each cluster. BSs are treated as hydrogen-burning MS stars; their spectra are selected from the Lejeune et al. (1997, 1998) stellar spectral library, and they are given physical quantities by fitting evolutionary tracks to their observed positions in the CMDs. The other stellar ingredients in a cluster are approximated with a Padova isochrone (Bertelli et al. 1994). The final ISED of a cluster is the combination of these two components. The BS contribution to the conventional ISEDs varies for different clusters depending on the basic quantities of the cluster and the BS component. Discussion of these issues is given in § 4. In § 5 the BS modification to the integrated properties of the SSP model in terms of broadband \( B - V \) color is presented, and the corresponding consequences for the age determination of an SSP are also considered. The concluding remarks on our work are presented in § 6.

2. THE WORKING SAMPLE

Photometric data of a large number of Galactic open clusters and their BS members were published by Ahumada & Lappaset (1995, hereafter AL95). This data set enables good access to the study of BS populations in open clusters. For reasons discussed below, only 27 Galactic open clusters of ages \( \geq 1 \) Gyr are selected from AL95 as our working sample. For the younger clusters, there is no clearly defined turnoff point; therefore, definite BS identification cannot be given, and because of the short lifetimes and typically low numbers of member stars, some phases in the CMD are not sufficiently populated to ensure good statistics.

The basic parameters of the selected clusters are given in Table 1, where columns (1)–(3) give the cluster name, right ascension, and declination (J2000.0); columns (4)–(7) are the ages, color excesses \( [E(B-V)] \), distance modula (DMs) and metallicities \( (Z) \) of the clusters; the \( N_{\text{BS}} \) (number of BSs) and \( N_2 \) values are listed in columns (8) and (9), respectively; and finally, column (10) is the reference number. Values of \( N_{\text{BS}} \) and BS photometric data for selected clusters are quoted directly from AL95. The \( N_2 \) values listed in column (9) in Table 1, defined as the number of stars within an interval of 2 mag below the turnoff point for a given cluster, are also from AL95. The other basic parameters of the selected clusters, specifically the age, \( Z \), \( E(B-V) \), and DM, are extracted from the more recent photometric and theoretical work when results newer than AL95 are available.

\( N_2 \) is regarded as a very important parameter that indicates the richness of the theoretical stellar component in the simple population synthesis scheme. For each cluster, this count is made from the same CMD from which the BSs are selected. Then the ratio \( N_{\text{BS}}/N_2 \) can be taken as a specific BS frequency in a cluster and can be used as a probe for the cluster internal dynamic processes concerning BS formation. Figure 1 is the cluster number distribution of 27 sample open clusters as functions of four different parameters: age, \( Z \), \( N_{\text{BS}} \), and \( N_{\text{BS}}/N_2 \). There are scarcely any very old clusters in our working sample; the oldest one is 8 Gyr. More than one-half of the clusters are metal-poor with respect to solar abundance. The metallicity distribution peaks at less than a half the solar value \( (Z \approx 0.007) \). The cluster distributions in both \( N_{\text{BS}} \) and \( N_{\text{BS}}/N_2 \) are inclined to low numbers, which means that the clusters have a large number of neither member stars nor BSs. Only two clusters possess more than 30 BSs. The ratio of \( N_{\text{BS}}/N_2 \) is confined in a region between 0.05 and 0.25. Figure 2 shows the BS numbers for our sample clusters as functions of cluster age and \( N_2 \) number, where there is no indication of any correlation between \( N_{\text{BS}} \) and cluster age (Fig. 2a), while a good correlation with \( N_2 \) is well defined (Fig. 2b).

It is worth emphasizing here that not all the clusters have complete membership determinations in terms of both proper motion and radial velocity. The selection of BS candidates in AL95 is basically according to where the appear in the observed CMDs. In our work, all the BSs are treated equally, without any further detailed membership measurements and BS identification. Such a treatment inevitably suffers some problems, which will be addressed in § 4.

3. THE SYNTHETIC SED OF THE CLUSTER

An ideal SSP model could be applied to an open cluster in terms of metallicity and age of its members if all stars in it were
Table 1
Parameters of the Sample Clusters

| ID      | R.A. (J2000.0) | Decl. (J2000.0) | Age (Gyr) | E(B - V) | DM | Z   | N_{BS} | N_{2} | References |
|---------|----------------|----------------|-----------|----------|----|-----|--------|------|------------|
| Tombaugh 1 | 07 00 29     | -20 34 00     | 1.0       | 0.40     | 13.60 | 0.02 | 1      | 5     | a          |
| NGC 6208 | 16 49 28     | -53 43 42     | 1.0^b     | 0.18^b   | 10.55^c | 0.023^d | 5      | 60    | b, c, d    |
| NGC 2660 | 08 42 38     | -47 12 00     | 1.2       | 0.36     | 12.30 | 0.02 | 18     | 110   | e         |
| NGC 2158 | 06 07 25     | +24 05 48     | 1.2       | 0.55     | 15.10 | 0.006 | 30     | 150   | f         |
| NGC 6939 | 20 31 30     | +60 39 42     | 1.6       | 0.33     | 12.27 | 0.02 | 4      | 80    | g         |
| NGC 3680 | 11 25 38     | -43 14 36     | 1.6       | 0.075    | 10.20 | 0.026 | 4      | 18    | h         |
| NGC 752  | 01 57 41     | +37 47 06     | 1.7       | 0.035    | 8.25  | 0.014 | 1      | 25    | i         |
| NGC 2112 | 05 53 45     | +00 24 36     | 2.0^i     | 0.63^i   | 9.65^j  | 0.014^k | 15     | 80    | j, k      |
| NGC 7789 | 23 57 24     | +56 42 30     | 2.0       | 0.24     | 12.00 | 0.016 | 25     | 130   | l         |
| IC 4651  | 17 24 49     | -49 56 00     | 2.4       | 0.086    | 10.10 | 0.013 | 8      | 35    | m         |
| NGC 6819 | 19 41 18     | +40 11 12     | 2.5^b     | 0.16^b   | 12.35^n | 0.025^o | 33     | 270   | n, o      |
| Berkeley 19 | 05 24 06    | +29 36 00     | 3.0^p     | 0.40^p   | 13.50^p  | 0.008^q | 1      | 10    | p, q      |
| NGC 1252 | 03 10 49     | -57 46 00     | 3.0       | 0.02     | 9.04  | 0.02  | 1      | 7     | r         |
| NGC 2420 | 07 38 23     | +21 34 24     | 3.4       | 0.05     | 11.95 | 0.007 | 12     | 140   | s         |
| NGC 2506 | 08 00 01     | -10 46 12     | 3.4       | 0.05     | 12.20 | 0.007 | 12     | 130   | t         |
| NGC 2682 | 08 51 18     | +11 48 00     | 4.0       | 0.045    | 9.38  | 0.02  | 30     | 200   | u         |
| NGC 7142 | 21 45 09     | +65 46 30     | 4.5^x     | 0.35^x   | 11.40^x  | 0.016^w | 23     | 120   | v, w      |
| Melotte 66 | 07 26 23     | -47 40 00     | 4.5^k     | 0.16^k   | 13.75^k  | 0.008^y | 46     | 180   | x, y      |
| King 11   | 23 47 48     | +68 38 00     | 5.0^y     | 1.27^w   | 15.30^z  | 0.02^aa | 24     | 140   | z, aa     |
| NGC 2243 | 06 29 34     | -31 17 00     | 5.0       | 0.06     | 13.05 | 0.007 | 7      | 120   | bb        |
| King 2    | 00 51 00     | +58 11 00     | 6.0^ee    | 0.32^ee  | 15.20^z  | 0.01^f  | 30     | 250   | z, cc     |
| Berkeley 42 | 19 05 06    | +01 53 00     | 6.0       | 0.64     | 10.30 | 0.012 | 1      | 20    | dd        |
| Berkeley 32 | 06 58 06     | +06 26 00     | 6.3       | 0.08     | 12.60 | 0.012 | 19     | 150   | ee        |
| NGC 188   | 00 47 28     | +85 15 18     | 7.0^ff    | 0.09^ff  | 11.44^ff  | 0.024^gg | 20     | 170   | ff, gg    |
| NGC 6791 | 19 20 53     | +37 46 18     | 7.2       | 0.17     | 13.52 | 0.039 | 27     | 110   | hh        |
| NGC 1193 | 03 05 32     | +44 23 00     | 8.0       | 0.12     | 13.80 | 0.01  | 16     | 190   | ii        |
| Berkeley 39 | 07 46 42     | -04 36 00     | 8.0       | 0.12     | 13.40 | 0.01  | 29     | 220   | jj        |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

References.—(a) Carraro & Patat 1995; (b) Paunzen & Maitzen 2001; (c) Lindoff 1972; (d) Loktin et al. 1994; (e) Piersimoni et al. 1993; (f) Rosvick & Balam 2002; (g) Hozejurina-Platais et al. 1997; (h) Daniel et al. 1994; (i) Carraro et al. 2002; (j) Brown et al. 1996; (k) Friel & Janes 1993; (m) Anthony-Twarog et al. 1988; (n) Rosvick & Vandenbergh 1998; (o) Bragaglia et al. 2001; (p) Christian 1980; (q) Christian 1984; (r) Pavani et al. 2001; (s) Anthony-Twarog et al. 1990; (t) McClure et al. 1981; (u) Boyle et al. 1998; (v) Crinklaw & Talbert 1991; (w) Canterna et al. 1986; (x) Twarog et al. 1995; (y) Gratton & Contarini 1994; (z) Kaluzny 1989; (aa) Dias et al. 2002; (bb) Bergbusch et al. 1991; (cc) Aparicio et al. 1990; (dd) Aparicio et al. 1991; (ee) Richtler & Sagar 2001; (ff) Sarajedini et al. 1999; (gg) Worthey & Jowett 2003; (hh) Kaluzny & Rucinski 1995; (ii) Kaluzny 1988; (jj) Kaluzny & Richtler 1989.

Fig. 1.—Distributions of the open cluster sample according to four different parameters: age, Z, N_{BS}, and N_{BS}/N_{2}.
single (at least not interacting binaries) and the low-mass members were conserved against the tidal effects. Unfortunately, nature turns us down at this point. The obvious difference between an SSP and a real star cluster is the stars that result from interacting binaries, stellar collisions, and the evaporation of the low-mass components. In old open clusters, since there are large populations of RGB stars and red clump giants, the red stragglers can hardly alter the integrated light of an SSP, owing to their rarity and low luminosity compared with the RGB and the clump giants within the same cluster. Therefore, the most prominent features in the CMDs of open clusters are the luminous BSs.

Given the discussion above, the stellar population of a cluster is assumed to be composed of two components in our work. The first is a package of all the member stars fitted by an isochrone in the CMD plus the low-mass stars that have been peeled off by tidal effects. This is obviously nothing but the conventional SSP model, and it is referred to as the SSP component in the following text. The second includes all the other members that straggle away from the isochrone. In light of the discussion above, only BSs are included in this component. We label it the BS component.

Assuming that the cluster CMD can be well fitted by a theoretical model, the SSP component of a cluster can be substituted with the theoretical isochrone that best fits the age and metallicity of the cluster. On the other hand, the BS component is specified in the CMD using photometric data from AL95. Figure 3 shows the composite CMD of NGC 6791 as an example, where the solid line is the isochrone, the dotted line is the zero-age main-sequence (ZAMS), and the dots are the BSs defined by photometry. We notice that there are a number of objects located below the ZAMS loci. This is partly due to observational uncertainties.

3.1. Getting the Theoretical Spectra of the BSs

There is a growing consensus that the major mechanisms of BS production are mass-transfer and merger events in close binary systems or stellar collisions in dense environments (Schönberner & Napiwotzki 1994). The physically interactive processes in binary systems will transfer fresh hydrogen fuel from the hydrogen-rich envelope to the hydrogen-depleted or exhausted core and reignite it, which makes the remnants behave like MS stars (Benz & Hills 1987, 1992); therefore, BSs are treated as hydrogen-burning MS stars in our work. Their masses, luminosities, and effective temperatures can be determined by fitting their positions in the CMD with evolutionary tracks of higher masses than the turnoff. Given the effective temperature ($T_{\text{eff}}$) and surface gravity ($\log g$), a theoretical spectrum from the library (Lejeune et al. 1997, 1998) can be assigned to the BSs. This process is performed for all the BSs in our sample clusters.

As shown in Figure 3, there are some BSs located below the ZAMS. Except for possible photometric errors, their missing...
positions are most likely due to the helium enrichment in the atmosphere after merger events (Benz & Hills 1987, 1992). The intrinsic properties of these stars need more carefully observational studies. In our work, these low-luminosity BSs are not considered in computing the ISEDs of the clusters, since their contributions to the integrated light are even much lower than the stars in the turnoff region.

3.2. Getting the ISED of a Cluster

The purpose of our work is to build modified ISEDs based on the observations of open clusters, so the clusters as a whole will be treated as unresolvable stellar populations. Most of the cluster member stars can be in principle confined in the single-star evolution regime, including the unresolved binaries shown in photometric binary sequence in the CMDs. Since the SSP component is based on single-star evolution theory, we should emphasize here that the IMF applied to conventional SSP model should account for both the single stars and the photometric binary stars in the observational CMDs. For a given cluster of age $t$ and metallicity $Z$, assuming Salpeter IMF $\phi(m)$, the ISED of SSP component is

$$F_{\text{iso}}(\lambda, t, Z) = A \int_{m_1}^{m_2} \phi(m) f(\lambda, m, t, Z) \, dm,$$

where $f(\lambda, m, t, Z)$ is the flux of a star of mass $m$, age is $t$, and metallicity is $Z$. $A$ is a normalization constant that is fixed by the cluster richness parameter $N_{\text{Z}}$, and $m_u$ and $m_l$ are the upper and lower integration limits in the current context, $m_i$ is the initial mass of the most massive living star at the age of the cluster, and $m_f$ takes its usual meaning.

By using a Salpeter IMF, $A$ is derived from the formula

$$N = A \int_{m_1}^{m_2} m^{-2.35} \, dm = N_{Z},$$

where $m_1$ and $m_2$ are the initial masses corresponding to the two limiting magnitudes defined by $N_{Z}$, i.e., $m_2$ is the initial mass of a star exactly at the turnoff, and $m_1$ is the initial mass of a star whose magnitude is 2 magnitudes lower than that of the cluster turnoff point.

For the BS component, the integrated spectra $F_{\text{BS}}(\lambda, t, Z)$ is given by directly summing up the individual spectrum:

$$F_{\text{BS}}(\lambda, t, Z) = \sum_{i=1}^{N_{\text{BS}}} f_{\text{BS}}^{i},$$

where $f_{\text{BS}}^{i}$ is the theoretical spectrum for a BS and the index $i$ runs from 1 to $N_{\text{BS}}$. $N_{\text{BS}}$ is the total number of BSs in a cluster.

Finally, the ISED of a cluster in our work is the combination of the integrated spectrum of SSP component $F_{\text{iso}}(\lambda, t, Z)$ and that of BS component $F_{\text{BS}}(\lambda, t, Z)$.

4. BS MODIFICATION TO THE CONVENTIONAL ISED

As discussed above, there are several channels of BSs formation. Depending on the specific dynamical environment of the host clusters and the correlation with the richness of the cluster (see Fig. 2b), the BS populations in different clusters actually present very different properties. Therefore, BS effects on the final ISEDs also vary greatly among the clusters in our sample.

To demonstrate the effects of BSs on the conventional ISEDs in the case of open clusters, Figure 4 is given with the fluxes of the different ingredients; the abscissa is the wavelength in angstroms, the dotted line shows the integrated spectrum of the BS component, the dashed line shows that of SSP, and the solid line shows the total ISED (the combination of the SSP and BS components). In our work, the BS modifications to the conventional SSP model can be divided into three cases: in the first case normal stars dominate (Fig. 4a), in the second case BSs are important (Fig. 4b), and in the third case BSs dominate (Fig. 4c). Regardless of the specific cases, the existence of the BS population modifies all the integrated light of our sample clusters to some extent, and these alterations are inclined toward the UV and blue bands, which makes the spectra hotter. For each of different cases, the BS population possesses certain properties, i.e., location in the cluster, membership measurements,
and number richness, that are important in interpreting the strength of the BS effects on the final ISEDs. These situations are discussed separately below.

4.1. Case 1: Normal Stars Dominate

In our work, six of the 27 sample clusters, namely, Berkeley 19, NGC 752, NGC 2243, NGC 2420, NGC 2506, and NGC 6208, are in this category. In this case, BSs are generally located near the cluster turnoff point in the CMDs, and there are fewer BSs than turnoff-region stars, so that they cannot produce obvious contribution to the integrated light of the cluster (Fig. 4). Based on the physical parameters and photometric data of sample clusters and BSs in different work, specifications of the clusters are given below.

4.1.1. NGC 6208

The membership probabilities of the five BSs (as in AL95) in NGC 6208 are ambiguous. Three of the five BSs were classified as B stars and nonmembers by Lindoff (1972). The other two high-probability member BSs possess very low luminosities and are located below the ZAMS in the composite CMD. According to the discussion above, these two BSs can be ignored when building the ISED. After excluding the nonmember BSs, the ISED of this cluster suffers virtually no BS correction and a conventional SSP model is retained. In Figure 5 the filled circles represent the five BSs in NGC 6208. The open squares represent the nonmember BSs in Lindoff (1972).

4.1.2. NGC 2420 and NGC 2506

These clusters NGC 2420 ($l = 198^1, b = +19^6$) and NGC 2506 ($l = 230^6, b = +9^9$) have very similar physical parameters, and the richnesses for them defined by $N_2$ are pretty close: 140 for NGC 2420 and 130 for NGC 2506. Although both have $N_{BS}$ values of 12, the properties of BS populations are quite different. In AL95, the BSs data of NGC 2420 were selected from the photometric work of West (1967), covering a sky region of 7.5 around the cluster center. Four BSs were classified as field stars in that work. In contrast, all the BSs in NGC 2506 (McClure et al. 1981) have membership probabilities $p \geq 90\%$, based on the proper motion study in Chiu & van Altena (1981).

Figure 6 shows a comparison of BS distribution and ISED modification in these two clusters. In the CMD in left panel, the circles are BSs in NGC 2506, the triangles are BSs in NGC 2420, and the solid-line isochrone represents general stellar components in two clusters according to their similar ages (3.4 Gyr) and metallicities ($Z = 0.007$). Although the BS population in

![Fig. 5.—CMD of NGC 6208. Solid line: Theoretical isochrone. Dashed line: ZAMS. Filled circles: Five BSs of NGC 6208 listed in AL95. Open squares: Three nonmember BSs in Lindoff (1972).](image1)

![Fig. 6.—Comparison of BS distributions and ISED modifications between NGC 2420 and NGC 2506. The left panel is the CMD, where the solid line is the theoretical isochrone with age (3.4 Gyr) and metallicity ($Z = 0.007$), the dashed line is the ZAMS, filled circles are BSs in NGC 2506, and filled triangles are BSs in NGC 2420. In the ISED plot (right panel), the thick solid line is the ISED of isochrone plus BSs in NGC 2420, the thin solid line is the ISED of BSs in NGC 2506, the thick dashed line is the ISED of BSs in NGC 2420, and the thin dashed line is the ISED of BSs in NGC 2506.](image2)
NGC 2420 is generally brighter than that in NGC 2506, the larger $N_2$ value balances this difference and makes the final ISED of NGC 2420 similar to that of NGC 2506, as shown in the right panel in Figure 6.

4.2. Case 2: BSs Important

Over half of our sample clusters (Berkeley 32, Berkeley 39, Berkeley 42, IC 4651, King 2, King 11, Melotte 66, NGC 188, NGC 1193, NGC 2112, NGC 2660, NGC 2682, NGC 3680, NGC 6791, NGC 6819, NGC 6939, NGC 7142, and NGC 7789) belong to the second case, in which the BS component seriously modifies the cluster ISED (see Fig. 4b). This situation generally happens (1) when there is a large number of bright BSs in the cluster; (2) when $N_{BS}$ is small, but there are a few (sometimes even just one!) BSs that are much brighter than the cluster turnoff point; and/or (3) when the cluster is too underpopulated.

As mentioned in the above context, the BS contribution depends directly on the selection of these bright stars. Clearer identification from high-resolution photometric work certainly favors more accurate results. Metallicity is also a sensitive parameter of the BS contribution: a low-metallicity ISED obviously presents stronger flux at shorter wavelengths than a high-metallicity ISED (Schulz et al. 2002). Discussion of these problems in this case, with respect to some sample clusters, is presented in the following.

4.2.1. King 2

Thirty stars were cited as BSs in King 2 in AL95, which was based on the Johnson-Cousins $UBVR_{CCD}$ photometry of Aparicio et al. (1990), in which only BS candidates within the core radius are considered, in order to avoid the probable contamination by field stars. This cluster has a large $N_{BS}$ values (as shown in Fig. 7), and the effects of the BSs on the ISED of this cluster are obviously due to the large number of bright BSs.

4.2.2. NGC 6939

As shown in Figure 8, four stars were defined as BSs in NGC 6939 in Cannon & Lloyd (1969). Star 59 was mentioned as a BS in Geisler (1988) (“59” is the identification number of the star from the finding chart in the photometry section of that work, from which all the following identifying numbers are taken), although it was unlikely a member. In AL95, NGC 6939 has an $N_2$ value of 80, which is smaller than that of King 2 and bigger than that of NGC 3680; thus NGC 6939 has an intermediate richness in our working sample. In this situation, the effects of BSs on the ISED would be better attributed to the high luminosities of the BSs, since the $N_{BS}$ of this cluster is much smaller than that of King 2.

4.2.3. Berkeley 42 and NGC 3680

These two clusters have both small $N_{BS}$ and small $N_2$. The single BS in Berkeley 42 was selected from the CCD photometry of Aparicio et al. (1991). Four stars (29, 33, 43, and 56) were identified as BSs in NGC 3680 in AL95 on the basis of the photoelectric observations of Eggen (1969), who later (1983) identified stars 3, 29, 33, and 56 as BSs and stars 20 and 34 as “red stragglers” with $ubvy$ photometry. In the CCD photometry of Anthony-Twarog et al. (1991), stars 29 and 33 were considered probable cluster members, but star 56 is unlikely a member. Meanwhile, the important presence of binaries around the turnoff point of NGC 3680 was observed by Anthony-Twarog et al. (1991). As shown in Figure 9, there is a BS in both of the two clusters whose positions in the CMDs highly exceed the cluster turnoff, which contributes most of the light in the blue part of the ISED.

4.2.4. Melotte 66

Melotte 66 holds a very special position in our work. Whether it should be included in this case or not is still not certain. Based on the photoelectric and photographic photometry in Hawarden (1976), the BSs in Melotte 66 were selected in the central 7' region of the cluster. However, the BSs ISED plotted as a dotted line in Figure 10 is not any bluer than the conventional SSP spectrum, and therefore the $B - V$ color of the cluster is not modified (see Table 2), even though it has the largest $N_{BS}$ (46) of all the sample clusters.

Furthermore, we find that 40 BSs of the cluster have spectra that are redder rather than bluer than those of the turnoff. The
remaining six blue-spectrum BSs are all located within the 3' of ring I of Hawarden (1976). In Figure 11 the circles represent the blue-spectrum BSs. The triangles represent the red-spectrum BSs, which would be better classified as “yellow stragglers.” This complicated situation can be partially attributed to the significant metallicity dispersion in and around the turnoff region of the cluster (Twarog & Anthony-Twarog 1995), apart from the membership and observational uncertainty issues.

4.2.5. NGC 188

As one of the most-studied old open clusters, many aspects of NGC 188 have been studied, certainly including its BS population. All 20 BSs in AL95 were selected from rings I and II in the finding chart of Sandage (1962), with membership probabilities $p \geq 80\%$ (Dinescu et al. 1996). This BS number almost doubles the 11 from the earlier work of Eggen & Sandage (1969). All the BSs show obvious high central concentration.

In the work of Dinescu et al. (1996), nine of the 11 BSs in Eggen & Sandage (1969) were confirmed as cluster members with high probabilities, while the other two (D and I-102 in Sandage 1962) were excluded because of their 0% proper motion membership probabilities. Dinescu et al. (1996) selected 11 probable BSs with $P_\mu \geq 50\%$ and $P_{\mu,r} \geq 70\%$ ($P_{\mu,r}$ is proper motion membership probability, and $P_{\mu,r}$ is the combined probabilities of both proper motion and spatial distribution), which include five of Eggen & Sandage (1969) while adding six new BSs. Of the six new BSs, four are out of ring III and the other two are in ring II of Sandage (1962). Although it is the latest observation of the cluster, Dinescu’s BS catalog does not show a central concentration significantly higher than that of RGB stars and therefore the original AL95 catalog is still adopted in our work.

The BS population in this cluster has been followed intensively in the past. Although the membership properties of a few BSs are subject to dispute, the overall BS population still considerably modifies the total ISED of the cluster. This correction to the corresponding SSP model at the age and metallicity of NGC 188 is very convincing, given that it is based on so many theoretical and observational efforts.

4.2.6. NGC 2682

Like NGC 188, NGC 2682 (M67) has been regarded as a classical old open cluster because so much research has been done on it in almost every subject in stellar physics. The photometric data of its BSs in AL95 was from Sanders (1989), who had earlier derived the membership measurements for the cluster stars (Sanders 1977). Among the total 30 BSs in AL95, 22 were confirmed and two more were added by Deng et al. (1999) on the basis of photometric data of the Beijing-Arizona-Taipei-Connecticut (BATC) sky survey and membership data from Girard et al. (1989). Figure 12 is given here to compare
the possible discrimination between these two groups of BS identifications. In the CMD (left panel), the dots are BSs in AL95, and open rectangles are BSs defined by Deng et al. (1999). As shown in the right panel, there is no obvious difference in the ISEDs of these two BS identifications. This result confirms our previous work on how BSs modify the SSP model in this cluster (Deng et al. 1999).

4.3. Case 3: BSs Dominate

For the third case (Tombaugh 1, NGC 1252, and NGC 2158), there is at least one extremely luminous BS in the cluster and/or the cluster is extremely underpopulated. The BS(s) is so bright that it accounts for almost all the integrated light of the cluster (Fig. 4c). The situation in this case raises issues like membership probability of the bright star and the property of such a star if it is a member, just as the luminous BS F81 does in NGC 2682 (Deng et al 1999).

4.3.1. Tombaugh 1 and NGC 1252

AL95 gives only one BS for Tombaugh 1 (Turner 1983). It appears that the cluster is a faint system that is merely visible from the field background. Turner (1983) obtained photoelectric photometry for only 26 stars in the cluster region. In the finding chart of Turner (1983), the BS locates near but outside ring I, which has a radius of 5'. In the CMD of Tombaugh 1 (Fig. 13, left), it lies more than 1 mag higher than the cluster turnoff point. In the ISED (Fig. 13, right panel), this single BS contributes about 70% of the total ISED. Especially at wavelengths shorter than 3000 Å, it provides almost all the

| ID        | Age (Gyr) | Z   | N_2 | N_{BS}^a | N_{BS}^b | (B − V)_{iso} | (B − V)_{iso+BS} |
|-----------|-----------|-----|-----|----------|----------|---------------|------------------|
| Tombaugh 1| 1.0       | 0.02| 5   | 1        | 1        | 0.285         | 0.615            |
| NGC 6208  | 1.0       | 0.0023| 60  | 3        | 3        | 0.596         | 0.626            |
| NGC 2158  | 1.2       | 0.006| 150 | 30       | 30       | 0.333         | 0.519            |
| NGC 2660  | 1.2       | 0.02 | 110 | 18       | 18       | 0.460         | 0.444            |
| NGC 6939  | 1.6       | 0.02 | 80  | 4        | 4        | 0.474         | 0.743            |
| NGC 3680  | 1.6       | 0.026| 18  | 4        | 4        | 0.608         | 0.752            |
| NGC 752   | 1.7       | 0.014| 25  | 1        | 1        | 0.671         | 0.713            |
| NGC 2112  | 2.0       | 0.014| 80  | 15       | 14       | 0.543         | 0.756            |
| NGC 7789  | 2.0       | 0.016| 130 | 25       | 24       | 0.487         | 0.763            |
| IC 4651   | 2.4       | 0.035| 35  | 8        | 7        | 0.646         | 0.856            |
| NGC 6819  | 2.5       | 0.025| 270 | 33       | 32       | 0.678         | 0.835            |
| Berkeley 19| 3.0       | 0.008| 10  | 1        | 1        | 0.790         | 0.795            |
| NGC 1252  | 3.0       | 0.02 | 7   | 1        | 1        | 0.263         | 0.849            |
| NGC 2420  | 3.4       | 0.007| 140 | 12       | 12       | 0.764         | 0.771            |
| NGC 2506  | 3.4       | 0.007| 130 | 12       | 11       | 0.769         | 0.771            |
| NGC 2682  | 4.0       | 0.02 | 200 | 30       | 21       | 0.762         | 0.914            |
| Melotte 66| 4.5       | 0.008| 180 | 46       | 46       | 0.823         | 0.823            |
| NGC 7142  | 4.5       | 0.016| 120 | 23       | 22       | 0.634         | 0.879            |
| NGC 2243  | 5.0       | 0.007| 120 | 7        | 7        | 0.802         | 0.819            |
| King 11   | 5.0       | 0.012| 140 | 24       | 12       | 0.683         | 0.858            |
| King 2    | 6.0       | 0.01 | 250 | 30       | 30       | 0.681         | 0.858            |
| Berkeley 42| 6.0      | 0.012| 20  | 1        | 1        | 0.645         | 0.872            |
| Berkeley 32| 6.3      | 0.012| 150 | 19       | 18       | 0.645         | 0.873            |
| NGC 188   | 7.0       | 0.024| 170 | 20       | 17       | 0.841         | 0.960            |
| NGC 6791  | 7.2       | 0.039| 110 | 27       | 18       | 0.799         | 1.028            |
| NGC 1193  | 8.0       | 0.01 | 190 | 16       | 15       | 0.777         | 0.896            |
| Berkeley 39| 8.0      | 0.01 | 220 | 29       | 28       | 0.749         | 0.896            |

*a The original BS number listed in AL95.

*b The BS number adopted in our work, eliminating the BSs below the ZAMS.

**TABLE 2**

**COLOR MODIFICATIONS OF THE CLUSTERS**

![Table 2](image-url)

Fig. 11.—CMD of Melotte 66. Solid line: Theoretical isochrone according to the given age (4.5 Gyr) and metallicity (Z = 0.008). Dashed line: ZAMS. Circles: Six blue-spectrum BSs in the cluster. Triangles: Forty red-spectrum BSs.
integrated light of the cluster. In this instance, the BS is not much brighter than the turnoff, and the overwhelming effect of the BS is completely due to the underabundance of the cluster members. Meanwhile, a B9.5 V star is identified as the only confirmed BS in NGC 1252 on the basis of the photometric study by Bouchet & The (1983). It suffers the same problem as Tombaugh 1, having both very small $N_{BS}$ and very small $N_2$ (see Table 1). We argue that in this case, more detailed photometric work and membership measurements are inevitably needed to identify BSs. For the moment, the ISED derived in this case is considered to be a superficial exercise whose implication on the conventional SSP model corresponding to the age and metallicity of the cluster has little statistical significance.

4.3.2. NGC 2158

Using the photoelectric photometry of Arp & Cuffey (1962), AL95 cited 30 stars as BSs in NGC 2158. Among them, 22 are located in the central region of the cluster (rings I and II), while the other eight are scattered in rings III and IV. Four BSs were confirmed as double stars by Arp & Cuffey (1962), including the brightest BS of the cluster (located in ring II), which is marked “D1” in Figure 14. D1 is more than 4 mag brighter than the cluster turnoff point. This magnitude gap exceeds the maximum limit for BS predicted by the mass-transfer theory (McCrea 1964), just like F81 for M67 (Wheeler 1979). A new model is needed to interpret such a location of a BS in the CMD if such a star is a real member of the cluster.

\[ \text{Fig. 12.—Comparison with BS identifications of NGC 2682 in two works. In the CMD, dots represent the BSs in Sanders (1989) and open rectangles are for the BSs in Deng et al. (1999). In the ISED, the solid line is the integrated light of the BSs in Sanders (1989) and the dashed line is that in Deng et al. (1999).} \]

\[ \text{Fig. 13.—CMD and ISED of Tombaugh 1.} \]
To show the alteration of these bright stars relative to the conventional SSP model, Figure 15 is given here to show the flux of BSs in different combinations in NGC 2158. The thick solid line is the conventional ISED corresponding to the isochrone only. The other four lines show different BS combinations: the long-dashed line represents the isochrone plus all the BSs except D1; the short-dashed line shows the spectrum of D1 alone; the dotted line is for the total BSs contribution; and the thin solid line is for the isochrone plus all BSs. As shown in Figure 15, D1 dominates the ISED from the UV to the near-IR wavelengths. It contributes almost all the energy at spectra shorter than 1500 Å, about 80% of the integrated light of all BSs up to 4000 Å, and still around 50% up to 7000 Å and beyond.

5. MODIFICATIONS TO ISED IN TERMS OF BROADBAND B−V COLOR

Although the effects of BSs on SSPs’ ISEDs have been clearly demonstrated by the spectral alterations of composite clusters, in practice broadband color is more frequently used when trying to understand unresolved stellar populations in galaxies. Compared with the conventional SSP model, BSs turn the spectrum bluer. The photometric bluer color in nature corresponds to the younger stellar populations; in other words, the age will be underestimated when fitting the color with the conventional SSP model. In terms of the modification to broadband B−V color, the BS correction on the SSP model can be quantified.

5.1. B−V Color versus Age

The integrated color of a theoretical SSP changes with time when massive stars leave the blue and luminous MS. Here the most intuitionistic trend in the picture of conventional SSP model is that the color becomes redder. However, the common existence of BSs will put a different signature on this scenario. In our work, the “observed” B−V color with BS effects is quite a bit bluer than that predicted by the conventional SSP model. Figure 16 depicts such a modification. Theoretical B−V color of four different metallicities is given by four lines of different types, obtained by convolving the conventional ISEDs made with standard SSP model (assuming a Salpeter IMF and using the Padova stellar track library) with corresponding filter responses. The filled circles show the B−V color (derived with the combined ISEDs) of the 27 sample clusters involving BSs contribution. It is clearly shown that the B−V color has been dramatically modified by BSs. All the solid circles lie...
below the theoretical value of $Z = 0.02$, although 40% of the sample clusters are metal-rich ($Z > 0.02$). The three lowest points in Figure 16 are those for BS-dominated clusters. As discussed in § 4, quantitative analysis of BS effects on this kind of cluster should be supported by further studies both in observation and theory. Detailed results are listed in Table 2. Columns (1)–(3) give the name, age, and metallicity of the cluster (the age and metallicity parameters are from the same sources as in Table 1). Column (4) is for $N_2$. Column (5) gives the original BS number listed in AL95, while column (6) lists the BS number adopted in our work (eliminating the BSs below ZAMS). Finally, columns (7)–(8) list the $B - V$ colors resulting from the conventional SSP model and from the BS-corrected model, respectively.

Assuming that all the sample clusters have solar metallicity ($Z = 0.02$), Figure 17 shows quantitatively the age underestimation when fitting the photometric data with the conventional SSP model. The solid line in Figure 17 plots the theoretical $B - V$ color of $Z = 0.02$ against the age of our sample clusters. Keeping the $B - V$ color the same while doubling the age, we get the dashed line, and when we quadruple the age, we get the dotted line. In Figure 17 the smallest deviated points in color can be approximated by increasing the age of conventional SSP model by about 30% (long-dashed line), and the double-age dashed line runs through many of the BS-corrected filled circles.

5.2. $B - V$ Color versus Metallicity

As described in § 2, there is a nonnegligible metallicity dispersion in our sample clusters. More than half of them are metal-poor ($Z < 0.02$). Since metallicity is an essential parameter for the evolution of both stars and galaxies, it will inevitably influence the intrinsic properties of BSs and therefore change the BS effects on the conventional SSP model.

In this work, the possible impact of metallicity on the BS contribution is detected with the corrected $B - V$ colors as a function of cluster metallicities. The corresponding details are pointed out in Figure 18, where the ordinate is the ratio of $B - V$ alterations caused by the BS component in a cluster to the theoretical $B - V$ color of conventional SSP model (or named relative alterations), and the abscissa is the metallicity of our sample clusters. It seems from Figure 18 that cluster metallicity and BS contribution are well correlated in the metal-poor case. This is simply stressed in Figure 19 with four typical $Z$ values ($Z \leq 0.02$), each of which has no fewer than three

FIG. 17.—Detecting age underestimation of star clusters when fitting the observed color with conventional SSP model. Assuming all the sample clusters with solar metallicity, the solid line is theoretical $B - V$ color. The dashed line represents when the $B-V$ values are kept the same and the age is doubled, and the dotted line is for when the age is quadrupled. The long-dashed line is plotted with age increased by 30% over the conventional value.

FIG. 18.—Correlation between metallicity and the ratio of the alteration of $B - V$ color caused by BSs to the conventional $B - V$ color.

FIG. 19.—BSs contribution to cluster $B - V$ color, presented with four metallicities: $Z = 0.007$, $Z = 0.01$, $Z = 0.012$, and $Z = 0.02$. 

No. 2, 2005  BLUE STRAGGLERS AND INTEGRATED SEDs  835
samples in this work. In Figure 19 the relative alterations in $B/C_0$V color increases with metallicity. However, such a correlation does not appear in the case of $Z > 0.02$. We need a complete working sample for this analysis.

5.3. Fitting the ISEDs of Open Clusters with the Conventional SSP Model: Uncertainties

Based on the expatiation in above paragraphs, the conventional SSP model derived from single-star evolution theory is dramatically altered by the BS component in a population. This modification typically enhances the UV and blue parts of the ISEDs, and therefore the $B-V$ color of SSPs becomes bluer. If it is used to derive an age for a population including BSs by fitting a conventional SSP model, there will be a substantial uncertainty. This conclusion can be visualized by directly fitting the real ISED of a population with the conventional ISED model with either depressed age or depressed metallicity, since both factors make the ISED bluer, as do the BS components in

Fig. 20.—Fitting the composite ISED of NGC 188 with the conventional SSP model. The abscissa is the wavelength in angstroms. The ordinate is the log (flux), which is the logarithmic value of the absolute flux of the ISED, and is normalized at 5500 Å. The difference between the composite and conventional ISEDs, $\delta$, is the direct subtraction of these two fluxes. Standard deviation $\sigma$ is given in dotted lines in $\pm 3\sigma$. The left panel is the fitting result of keeping the same metallicity but using a younger age, while the right panel is that just the opposite, keeping the same age but using a lower metallicity. The composite ISED is plotted with a solid line. The conventional ISED is given by the dashed line. The basic parameters of the cluster adopted in our work are listed in the top right corner in each panel. The parameters of the conventional ISED are given below the fitting line.

Fig. 21.—Similar to Fig. 20, but for NGC 2682.
the case of our sample clusters. In other words, ignoring the existence of BSs in stellar populations of the metallicity and age ranges covered by our sample may cause one to seriously underestimate either the age or the metallicity of the population by the conventional SSP model.

In this work, the composite ISEDs of open clusters including BSs contribution are fitted with the conventional SSP model at younger ages or lower metallicities. A quantitative measure of the uncertainties introduced by BSs in a population can be given in this way.

Taking the most popular old open clusters, NGC 188 and NGC 2682, as examples, the best-fit results are presented in Figures 20 and 21, respectively. The abscissa is the wavelength in angstroms. The ordinate is the logarithmic value of the absolute flux of ISED normalized at wavelength of 5500 Å. In the lower parts of the figures, the difference between the composite ISED of the cluster and the best-fit conventional SSP ISED is given as δ, together with the standard deviation σ in the region of ±3 σ (dotted lines). In each figure, the left panel is the fitted result that keeps the metallicity the same but uses a younger age, while the right panel is the opposite, keeping the same age but using lower metallicity. The composite ISED of the cluster is plotted by the solid line, and the conventional ISED is given by the dashed line. As a comparison, the basic parameters of the cluster adopted in our work are given in the top right corner in each plot. The parameters of the fitted conventional ISED is given just below the fitting line.

As shown in Figures 20 and 21, conventional SSP model can fit perfectly most of the features of the composite ISED of the cluster if we let the age or metallicity be free parameters. The exception is at the extreme-UV part of the SED. As we can see cluster if we let the age or metallicity be free parameters. The fit perfectly most of the features of the composite ISED of the cluster is plotted by the solid line, and the modified ISED of the cluster.

As shown in Figures 20 and 21, conventional SSP model can fit perfectly most of the features of the composite ISED of the cluster if we let the age or metallicity be free parameters. The exception is at the extreme-UV part of the SED. As we can see cluster if we let the age or metallicity be free parameters. The fit perfectly most of the features of the composite ISED of the cluster.

6. SUMMARY AND DISCUSSIONS

We study 27 Galactic open clusters older than 1 Gyr and their BS contents in this work to detect the effects of BSs on the integrated properties of the conventional SSP model. In general, the ISEDs of our sample clusters have been dramatically modified, and these modifications are emphasized in the UV and blue bands. In terms of photometry, the integrated B − V color of the sample clusters becomes bluer, and this leads to an underestimation either in age or in metallicity when fitting the observed colors of a target unresolved population with that of a conventional SSP model. The present results are summarized and discussed in the following:

1. In this work 27 Galactic open clusters older than 1 Gyr are selected as our working sample. Photometric data of the BSs, including B − V colors, V-band magnitudes, N_{BS}, and N_{2}, are quoted directly from AL95. The basic parameters of sample clusters from the recent literature are used when they are available.

2. We scheme a semiempirical approach of building cluster ISEDs. The general stellar ingredients including all member stars well fitted by a theoretical isochrone are represented by the conventional SSP model. BSs are treated as hydrogen-burning MS stars. Their positions in the CMD are fitted with evolutionary tracks of masses higher than the turnoff. Then, a theoretical stellar spectrum is assigned to each BS, according to parameters (T_{eff} and log g) derived from the best fitting. Finally, the combination of these two components constructs the modified ISED of the cluster.

3. We have divided the BS modifications to conventional ISEDs into three cases, namely, when normal stars dominate (Fig. 4a), when BSs are important (Fig. 4b), and when BSs dominate (Fig. 4c). The modifications are mainly related to the BS richness in the clusters and their positions in the observed CMDs. In the first case, BSs are generally located near the cluster turnoff in the CMD and the number of BSs is small when compared with turnoff region stars; therefore, they cannot produce an obvious contribution to the ISED of the cluster. In the second case, BS effects are enhanced generally because (a) there is a large number of bright BSs in the cluster; (b) the number of BSs is small, but there are a few (even just one!) that are much brighter than the cluster turnoff point; and (c) the cluster is very member-poor. The third case is an extreme situation. There is at least one extremely luminous BS in the cluster and/or the cluster is extremely poorly populated. The bright star(s) is so bright that controls almost all the integrated light of the cluster.

4. We have depicted the alteration of B − V color of our sample clusters caused by BSs. As shown in Figure 16, the B − V color becomes significantly bluer.

5. We have discussed the effects of metallicity on BSs contribution. As shown in Figure 18, they are well correlated in the metal-poor case (Z < 0.02). In Figure 19 the ratio of the alteration of B − V color increases with metallicity increasing. But the correlation does not follow the case of Z > 0.02.

6. We have scaled the age underestimation of a cluster by fitting the observed B − V color with the conventional SSP model. Based on the assumption that all the sample clusters have solar metallicity (Z = 0.02), we have shown in Figure 17 that the age of an observed stellar population is seriously underestimated by conventional SSP model. As clearly shown in Figure 17, 30% uncertainties in ages can be given for the least affected clusters, and for many cases, such corrections amounts to twice of the conventional age.

7. We have also detected the age and metallicity uncertainties when fitting the observed cluster ISED with conventional SSP model, since decreasing either age or metallicity will also make the ISED bluer, as does inclusion of BSs. Taking the old open clusters NGC 188 and NGC 2682 as examples, the results of the best fitting show that conventional SSP model can fit perfectly most of the features of the composite ISEDs including the BS contribution if we let the age or metallicity be free parameters, and both age and metallicity can change by a factor of 2.

8. The modifications to the theoretical SSP model corresponding to each cluster due to BSs show that BS population is very important and can be crucial for stellar population analyses of complex stellar systems. This is especially true when applying the current EPS technique to unresolved stellar systems. If we consider open clusters as typical descendants of regular star-forming activities and regulate our results to the age and metallicity ranges covered by present data set, the SSP model derived from single-star evolution theory is seriously altered. Therefore, the contribution of this component should be considered when applying EPS method to more complicated stellar systems.

The present results rely on photometry from different sources, and the formation mechanisms and the specific properties of BSs in each cluster in the sample vary greatly; therefore, we are limited to drawing our conclusion on the basis of a single cluster. With careful cluster physical parameter measurements and membership analysis of individual BSs, the current results are still meaningful and can be regarded as a reference for further investigation on this problem. To reveal the effects of
BSs on stellar populations in all different cases of age, metallicity, and environment, systematic observations together with simulations of stellar dynamical processes under all conditions are needed.

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