

Chapter 2

Researches of Stellar Populations in Star Clusters

2.1 Stellar Populations: We Think We Know Until Everything Change

SCs are the basic units for star formation [3]: almost all stars formed in clustered structures, most of them form following the turbulent structure of the interstellar medium (ISM) and collapse into bound clusters within a very short period (usually about one crossing time) [42, 43], a large fraction of those stars will gradually dissipate into the galactic field [4], populating the galactic stellar field. The SSP scenario assumes that this star forming process should resemble a single burst [20], this is because the strong initial stellar feedback, including the gas expulsion owing to energetic photons poured out from the most massive stars, strong stellar winds triggered by the first batch of Type II supernovae, will quickly exhaust all of the gas in the Giant Molecular Cloud (GMC), if a protocluster have exhausted its initial gas, its star forming process will stop rapidly.

2.1.1 *Why Most Clusters Should be Simple Stellar Populations?*

As introduced, the first topic confronting any underlying discussion of stellar populations is the initial star forming process in SCs. In principle, stars in a SCs should form in a single-burst channel unless they were initially extremely massive and compact: the strong stellar feedback would rapidly expel the initial gas, stopping the initial star-formation process. Timescale of the gas expulsion is very short, usually smaller than or comparable to the crossing time of a star cluster (~ 1 Myr), therefore the age range of first stellar population stars would be constrained in several million years as well. If there was a supernova explosion during the first several million years, all the gas will escape from the SC immediately, as a result, the clearance of molecular gas will quickly end the star formation in the SC. Assuming the typical time period for

the gas clearance is 1 Myr, given that the typical ages of most GCs (~ 10 Gyr) and YMCs (10–100 Myr) are much longer than this timescale, the star forming process in a star cluster can be thus treated as a burst mode. Despite the supernova explosion, the typical escape velocity of the initial gas is about 10 km s^{-1} during this stage, which is the sound speed of the ionized hydrogen (HII) gas, sometimes this velocity can exceed 10 km s^{-1} if the gas expulsion process was dominated by radiation pressure, which usually occurs in massive clusters [45].

During the period from 3–10 Myr, most O-type stars with initial masses of $\geq 16 M_{\odot}$ evolved off. These massive, quickly evolved stars will induce a large amount of energy into the ISM during their entire lifetime, which will unbind large amount of their surrounding gas. For example, A $15 M_{\odot}$ star would be able to eject 3×10^{50} erg per 0.1 Myr into the ISM, which will unbind $10^4 M_{\odot}$ gas within 1 pc region [46]. Because of this, a SC with age of ≥ 3 Myr should not contain a large fraction of residual gas, in addition, at this stage, the type II supernova explosion becomes frequent. The supernova explosions will expel its stellar material at a velocity of 10% of the speed of light ($\sim 3 \times 10^4 \text{ km s}^{-1}$), producing a shock wave through the ISM in their host SCs. Stimulated by the shock wave, the runaway velocity of the remaining gas in a SC will speed up to several hundreds or even thousands km s^{-1} . The multi-supernova explosions will sweep out all remanent gas in a SC immediately. Calculations have shown that only clusters who have their initial masses of $10^7 M_{\odot}$ to $10^8 M_{\odot}$ can survive the first series of supernova explosions [47].

Stars that are less massive than $\sim 8 M_{\odot}$ will be able to undergo the AGB phase, the stellar feedback in this stage is believed the most important part for the formation of secondary stellar populations: the AGB stellar winds eject the stellar material into the ISM, these chemical enhanced materials build the body of new generation stars. However, at the stage of when there are intermediate mass AGB stars, a SC should already at least 30 Myr old, the gas expulsion and type II supernovae must have already exhausted a large amount of initial mass. In the meantime, the cluster itself should already be expanded, thus loss the capacity to capture the subsequent AGB stellar wind. Such a “self-circle” scenario is based on the assumption that clusters have the capacity to retain the AGB ejecta after the period of gas clearance, which means only the initially most massive and compact clusters will be able to form secondary stellar populations in this stage. The typical velocities of AGB stellar wind is about 10 km s^{-1} to 100 km s^{-1} , which is even faster than the velocity of initial gas expulsion ($\sim 10 \text{ km s}^{-1}$ [46]). Only a cluster whose escape velocity is larger than this value at the age of ≥ 30 Myr would be able to preserve a gas-rich environment. Assuming an average half-mass radii for young clusters is ~ 1 pc, the escape velocity can be calculated through [48],

$$v_{\text{esc}}(t) \approx 0.1 \sqrt{\frac{M_{\text{cl}}(t)}{r_{\text{h}}(t)}} \text{ km s}^{-1}. \quad (2.1)$$

It immediately tells us that only clusters whose initial mass are between $10^4 M_\odot$ and $10^6 M_\odot$ can retain the initial runaway stellar material in their gravitational potential wells.

Figure 2.1 shows the minimum mass for clusters to keep their initial runaway material versus their current mass, this diagram contains two sub-panels for two different escape velocities: 10 km s^{-1} (top; roughly equal to the gas-expulsion velocity and the slowest AGB ejecta), and 100 km s^{-1} (bottom; the **lowest** escape velocity driven by Type II supernovae).

Figure 2.1 tells us that all the OCs that we observed are not be able to have secondary star formation after their initial star formation terminate. About half of the observed YMCs in our MW will failed to retain the slowest AGB ejecta, and when the Supernova explosions further accelerate the remaining gas, all the YMCs will lose their initial ISM and stop the star formation permanently if no additional material can be fuelled. GCs seem more ‘safe’ than OCs and YMCs, but most of them would also not be able to keep the runaway gas once the Type II supernovae began to affect the environment. This is a conservative estimation, because the escape velocity of 100 km s^{-1} is only a lower limit to the velocities generated by supernova explosions.

However, Fig. 2.1 only compares the clusters’ critical masses to their current masses not initial masses, for most OCs and all YMCs, this will not change anything because they may have unlikely undergone significant mass loss owing to their young age, but this may complicates the estimations of GCs’ initial masses. Mass loss caused by two-body relaxation can be evaluated through the formula [50],

$$\dot{m} \approx 1100 \left(\frac{\rho_h}{M_\odot \text{ pc}^{-3}} \right)^{1/2} M_\odot \text{ Gyr}^{-1}. \quad (2.2)$$

If assuming a typical age of 12 Gyr for GCs, then most GCs should be initially 10 to 15 times more massive than their current masses, that means they should have a strong capacity to keep their initial runaway gas in their infancy. It is unclear if young GCs could capture gas to form secondary stellar populations, because no observation has recorded a resolved YMC with this tremendous initial mass ($\geq 10^7 M_\odot$).

This is why SCs should be initially SSPs: their initial star-formation episodes can only have lasted before all their initial gas being expelled, i.e., the first-generation stars should have a very narrow age range because they can only form over a short timescale. After this stage, a survived cluster will become less compact and less massive, thus loses its capacity to retain additional gas like the materials contributed by subsequent intermediate mass AGB stellar wind. The observations of young SCs with ages $\leq 10 \text{ Myr}$ show that their member stars are usually embedded in a regions that are largely devoid of gas, while YMCs that are older than several tens of million years are all fully exposed.

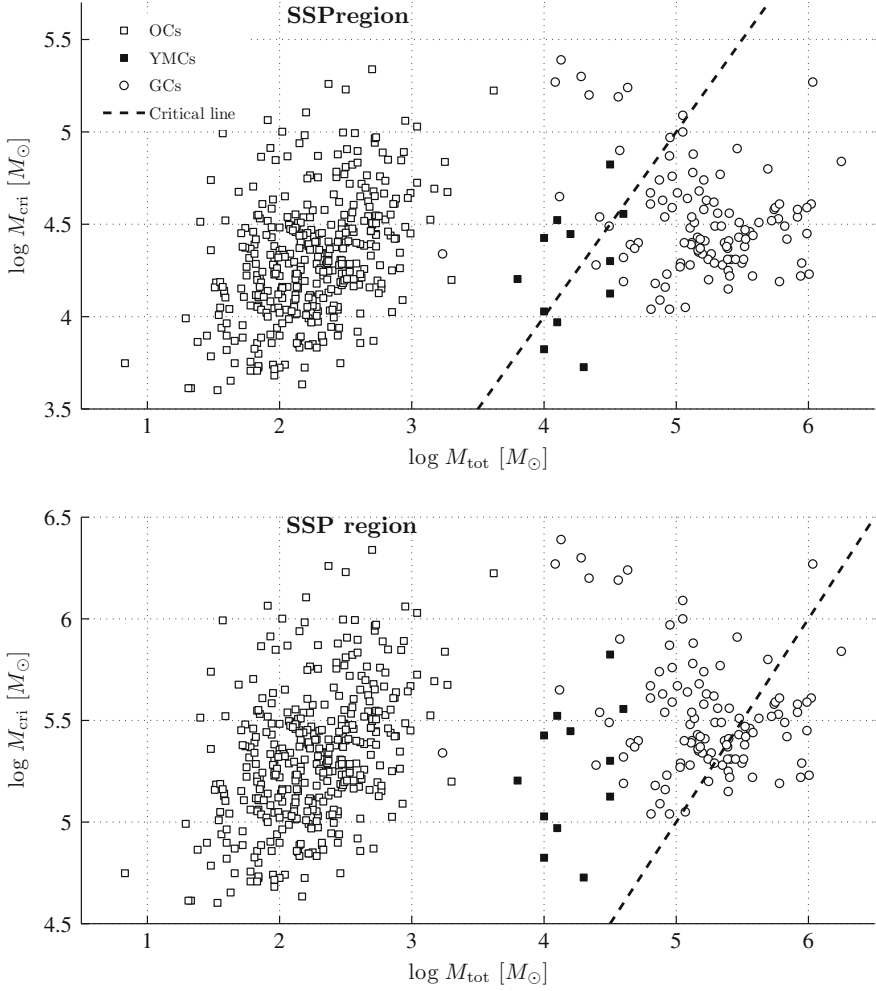


Fig. 2.1 Clusters' critical mass ($\log M_{\text{crit}}$) versus their actual mass ($\log M_{\text{tot}}$), here the critical mass is defined as the minimum mass that is required to capture the initial runaway gas for a cluster. Open squares, filled squares and *open circles* represent the Galactic OCs, YMCs, and GCs, respectively. OC and YMC data are from [10]. GC data are derived from [49]. The region that above the critical lines (black dashed line) represents the SSP region, that means SCs in this region will not be able to retain their initial runaway material based on their current masses. Escape velocities: (top) 10 km s⁻¹; (bottom) 100 km s⁻¹

2.1.2 Complicated Stellar Populations in Star Clusters

Almost all OCs are chemically homogeneous [51–53], this seems also hold for old OCs like NGC 188 [54], thus proving that their member stars were indeed coevally originated from a common GMC. Same conclusions also hold for stellar associations

and star-forming regions [55, 56], indicating a high degree of chemical homogeneity in primordial GMCs.

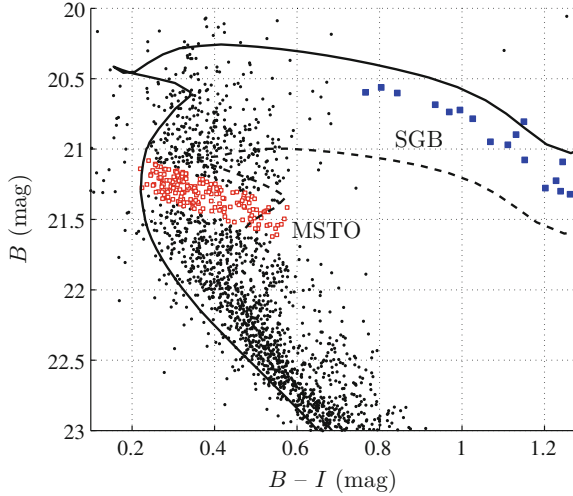
As introduced in Chap. 1, a direct method to examine if a SC is SSP is to study its CMD, the CMD of an SSP can be described by a single isochrone. However, because most OCs reside at the Galactic disk, their CMDs are usually messy owing to the extinction, making explorations of the age distributions of their member stars difficult. On the other hand, measuring a single star's age is still challenging based on current facilities and methods: no single approach can work for a broad range of stellar types in various ages, but this situation may change in the next few years once the technique of asteroseismology were improved [57].

Currently a main approach to study a single star's age is measuring its surface lithium abundance, because the lithium abundance is suggested to decrease with increasing stellar age. Studies based on this method have revealed that some stars seem to have ages that exceed the host OCs' isochronal ages [58, 59], but these exceptions only occupy a very small fraction of the first population stars, therefore they may not be able to resemble a large-scale ongoing star formation. To study the age range of a large stellar sample, a more promising approach is to explore the color-magnitude distribution of MSTO stars. The OCs Hyades and Praesepe, seem to possess their MSTO regions with apparent luminosity spread, indicating that their member stars may have age ranges span several hundred million years [60]. A similar result was found in the Orion Nebula Cluster, which seems harbor an internal age spread on the order of 10 Myr [61]. Similar results also appear in extragalactic YMCs, a recent study has found that a LMC YMCs, NGC 1856, displays an apparent extended MSTO (eMSTO) region [62], suggesting an initial SFH last for ~ 150 Myr. Another LMC YMC, NGC 1850, was also found to harbor an eMSTO, indicating an age spread of ~ 70 Myr [63]. Because both NGC 1850 and NGC 1856 belong to the LMC, differential extinction can not be responsible for their eMSTO regions, the discovery of broadened MSTO regions in YMCs seems to be a 'smoking gun' that supports stars in SCs can form continuously rather than born in an single star-burst.

For the CMDs of intermediate-age (1–2 Gyr) SCs in the LMC and SMC, the eMSTO is an ordinary feature: for instance, the LMC cluster NGC 1846 was found to possess a split in its MSTO region, indicating the presence of two stellar populations with ages of 1.5 Gyr and 1.8 Gyr, respectively [64], similar results were also found in LMC cluster NGC 1783 and NGC 1806 [65], with indications of their age dispersions should be at least 300 Myr. A comprehensive study shows that about 70% of the LMC intermediate-age SCs have eMSTO regions, which is in conflict with the expectations from SSPs [66]. Studies also show that for two SMC clusters, NGC 411 and NGC 419, their eMSTO regions are even consistent with an age spread of ~ 700 Myr [67]. In addition, NGC 419 also displays a dual RCs, which again indicates an extended age distribution [68].

However, a series of objections to the eSFH scenario were proposed, based on very solid negative results. An analysis of LMC cluster NGC 1831, a ~ 800 Myr cluster, have encountered an apparent conflict between the age spread derived from its eMSTO region and that implied by the compact RC [69]. Researches also extended to YMC candidates in local group galaxies other than LMC and SMC: a 570 Myr

Fig. 2.2 The CMD of NGC 411 with best fitting isochrones (*black dashed and solid lines*), which indicates an age spread of ~ 800 Myr [75], the *blue* filled squares and *red* open squares represent the samples of SGB stars and eMSTO stars, respectively



unresolved YMC candidate, NGC7252-W3, shows no evidence of eSFH, although it has an escape velocity of 193 km s^{-1} [70]. A survey for residual gas in 13 LMC and SMC YMCs with ages ≤ 300 Myr also denies any presence of residual gas in those YMCs [22], thus confirms that most YMCs in LMC and SMC may not be able to accrete large gas reservoirs to support ongoing star formation. On the other hand, if the eMSTO stars in these LMC and SMC clusters represent the same feature of MSPs in GCs, their member stars should show the well-know Na-O anticorrelation, however, a study on NGC 1806 report a negative result: no evidence of Na-O anticorrelation was found in the member stars of NGC 1806 [71], which indeed stands in marked contrast to the chemical variations present in GCs.

Numerous debates also focus on whether other features in the CMDs of intermediate-age SCs would be consistent with an eSFH. Li et al. (2014) claimed that in the 1.7 Gyr-old cluster NGC 1651, its SGB morphology can only be reconciled with an age spread of ≤ 160 Myr, which is much smaller than that derived from its apparent eMSTO region—450 Myr [72]. Their conclusion was subsequently confirmed in clusters NGC 1806 and NGC 1846 [73]. But an objection have argued that the morphology of SGBs in these clusters are actually consistent with an age spread scenario, if adopt a significant level of stellar convective overshooting to these SGB stars [74]. The dispute is ongoing, Li et al. (2016) discovered a very tight SGB in NGC 411, which can only be explained by an SSP [75]. As NGC 411 was claimed to harbor an age spread of ~ 700 Myr [67], which immediately produces an discrepancy with respect to the observed SGB. Figure 2.2 presents the CMD of NGC 411, which is already zoomed in the regions of eMSTO and SGB, two isochrones are required to describe the blue and red boundary of its eMSTO region, which indicates an age spread of ~ 800 Myr. It can be found that although the MSTO stars in NGC 411 were fully filled the region covered by these isochrones, almost all its SGB stars are alined with a narrow track, which actually corresponds to a single-aged isochrone.

Old GCs seem represent a different type of SCs. MSPs are believed to be a ordinary feature of the Galactic GCs (GGCs). Early evidence can date back to 1980s, where a dispersion in the CN-band strengths was found among seven MS stars in the GC 47 Tucanae (47 Tuc) [76], indicating that a process leading to N enhancement must have occurred in those stars, however, these MS stars themselves lack the capacity of mixing N to their stellar surface, the only explanation to the CN variation in these stars is they originated from the N-enhanced materials after the formation of N-poor stellar populations. Similar features were also detected in other GCs, like NGC 362 [77], NGC 6171 [78], NGC 6838 [79], NGC 5272 [80] and NGC 6205 [81, 280]. N-enhanced stellar populations also exhibit a strong absorption line at $\sim 3400 \text{ \AA}$, therefore affects their CMD morphologies in ultraviolet filters, producing a split in the RGB, this feature have been observed in a dozen GCs [82]. Other evidence of MSPs in GCs were reflected by the variations in light elements (Na, O, Mg, Al), as introduced, the Na-O anticorrelation is the most well-known relationship for GC stars. The Na-O anticorrelation in GCs is shown in both the MSTO, SGB, and RGB stars (e.g., [83–85]). The Na-O anticorrelation may caused by the processes of CNO circle ($\sim 20 \times 10^6 \text{ K}$) and Na proton-capture process ($\sim 35 \times 10^6 \text{ K}$), this anticorrelation seems unlikely the result of stellar evolution because the central temperatures of the stars in GCs ($\sim 0.85 M_{\odot}$) is too low to trigger these processes [32]. It looks like that all GGCs have Na-O anticorrelations, in addition, light-element variations are also detected in some LMC GCs [86]. Beside the Na-O anticorrelation, another relationship of Mg-Al anticorrelation has also been found in GCs (e.g., [87, 88]).

The iron abundance ([Fe/H]) dispersion, once appear in a cluster, would indicate that its SFH survived multi-supernova explosions, because only the ejecta of massive, core-collapse supernovae are able to enhance the iron abundance of ISM. There are lines of evidence show that at least some GCs have their member stars with dispersions of [Fe/O], like NGC 6656 (M22, [89]) and NGC 7089 (M2, [90]). This strongly suggests that at least some GCs have experienced much more complex SFHs. Precise photometry provide more impressive evidence, stellar populations with different elemental abundances, also show different properties in the CMDs: NGC 1851 was found to harbor dual SGBs in the CMD, different CNO contents were detected in stars belong to these two branches [92]. The GC NGC 2808 shows a triple MSs, indicating three stellar populations with helium-abundance of $Y = 0.248$, $Y = 0.30$, and $Y = 0.37$, respectively [93]. A recent study on NGC 7089 (M2) even reported seven stellar populations [94].

Because the photometric analyses usually involve stellar samples with much larger sizes than that explored by spectroscopic analyses, investigating the kinematics and dynamics of the different stellar populations becomes possible. Milone et al. [95] revealed dualities in the MS, SGB, and RGB of GC 47 Tuc, they explained these two stellar populations by a CN-weak, O-rich, Na-poor and normal helium abundances ($Y \sim 0.25$) stellar and a stellar generation with CN-strong, O-poor, Na-rich and enhanced helium abundances elemental abundances ($Y \sim 0.265$), they defined the former as first stellar population and the latter as secondary stellar population, respectively. They found that the secondary stellar population is more concentrated

than their first stellar population counterpart. Their conclusion is cemented through near-infrared observations [96, 201]. Similar results were also found in NGC 362 [97] and other GCs [98]

2.2 Proposed Scenarios

2.2.1 *The Extended Main Sequence Turn-Off Regions in Star Clusters*

As repeatedly mentioned, the most straightforward explanation to eMSTOs that observed in lots of LMC and SMC SCs is to assume they have experienced much longer initial SFHs, usually last for *at least* 300 Myr [66]. Goudfrooij et al. (2014) [100] proposed a scenario involves a prolonged round of SFH for massive clusters: the central escape velocities of the star clusters were high enough to accrete a large amount of pristine gas during the gas expulsion stage or to retain the ejecta of intermediate mass AGB stars and massive binaries. Most of this gas reservoir would be accumulated in the central regions of the clusters and form secondary stellar populations. This process may last several million years until all gas is exhausted by star formation or multiple supernova explosions. However, the discovery of no gas residual in YMCs invalidates this scenario [100]. Another possible solution to the suspected age spread in these LMC and SMC clusters invokes the merger, the merger between two clusters with different ages [64] or between a cluster and a star-forming GMC [101] would be able to explain the observed eMSTO in SCs, which may indicates that there was initially a large fraction of binary SCs in LMC and SMC, because of the fraction for SCs who harbor eMSTO regions is very high (70% [66]).

The age spread model strongly indicates that it is time to relinquish the SSP scenario for the formation of these relatively young SCs, however, there is another scenario directly denies the MSPs in these clusters, this scenario attributes the observed eMSTO regions to the results of stellar self-rotation. Stellar rotation can alter the morphology of MSTO regions in two channels: (i) the centrifugal force resulting from rotation reduces the stellar self-gravity, decreasing the surface effective temperature, that means a fast rotator should appears redder than its non- or slow-rotating counterpart (if they have the same mass). The reduced self-gravity also lead to a reduction of stellar luminosity as it reduces the stellar central nuclear reaction rate. Because the rotating mainly affect a star's equatorial region, which would make a rapidly rotating star look redder around its equatorial region than near its poles. This effect is defined as 'gravity darkening'; (ii) Rotation would enlarge the stellar convective cores, transporting hydrogen from the outer layers into the stellar center, replenishing the central fuel for hydrogen burning, which will thus prolong the stellar main-sequence lifetime. Once the massive, fast-rotating stars have comparable MS lifetime to less massive stars, a mass spread in the turn-off region of a stellar

population appears, resulting a luminosity dispersion in its turn-off region. This is called ‘rotational mixing.’

The less massive stars ($\leq 1.2M_{\odot}$) are not expected to become fast rotators owing to a mechanism called ‘magnetic braking’ [102, 103], i.e., the stellar magnetic field will lead the angular momentum steadily transfer away from the star through exerting a torque on the ejected matter during a star’s evolution. It has been confirmed that stars earlier than F0-type can easily reach an average rotational velocity of 100–200 km s⁻¹, while the G0-type stars’ typical rotational velocity is only 12 km s⁻¹ [104]. A study of a large number of B–F-type solar-neighborhood stars has confirmed that most of these stars are fast rotators [105].

In 2009, Bastian and de Mink [106] had proposed a scenario that rapid stellar rotation of F-type stars may lead to the misconception that intermediate-age SCs harbor dramatic age spreads. But their scenario has only considered the gravity darkening as the effect that is responsible for the extent of the eMSTO region. However, Girardi et al. [107] showed that rotational mixing will mitigate the broadening caused by gravity darkening, eventually leading to a narrow MSTO, therefore stellar rotation cannot be the (only) solution of the eMSTO. However, their conclusion was pointed out to has adopted an unrealistic convective mixing efficiency, it was found that the collective effects of gravity darkening and rotational mixing with a moderate mixing efficiency could produce the eMSTO region for 1–2 Gyr-old clusters [108]. A corollary of their results is that the MSTO area in a cluster would depend on its actual age, Fig. 2.3 presents the correlation between the FWHM of the clusters’ age spreads and their typical ages for coeval stellar populations, based on the Fig. 8f of Yang et al. [108].

If the age spreads of several hundred million years are valid for YMCs (≤ 300 Myr), a fraction of pre-main-sequence stars should appear in YMC CMDs, this is because their age distributions of member stars would scatter to zero age. However, as shown in Fig. 2.3, the internal age spreads of YMCs derived from their MSTO regions only occupy small fractions of their ages, this supports the stellar rotation scenario again, as it will partially broaden the MSTO region.

The relative importance of gravity darkening and rotational mixing in SCs is unclear because of the lack of direct observational evidence. To distinguish between these two effects, one promising approach is to study the loci of the rapidly rotating population on the CMD. Gravity darkening will produce an eMSTO where most fast rotators lie to the red side of the MSTO, while rotational mixing will lead most fast rotators to reside toward the blue side of the MSTO region. Another important feature that may shed light on this issue is the SGB. Because gravity darkening does not produce a mass spread among MSTO stars, once the MSTO stars have evolved off the main sequence, they will decelerate due to the conservation of angular momentum, the coeval MSTO population characterized by different stellar rotation rates will subsequently converge into a narrow SGB. On the other hand, the rotational mixing effect would produce a mass spread among evolved stars, broadening both the MSTO and SGB regions. If a fast rotating population is dominated by rotational mixing effect, it may display a broadened MSTO region and a SGB that largely dispersed in luminosity as well.

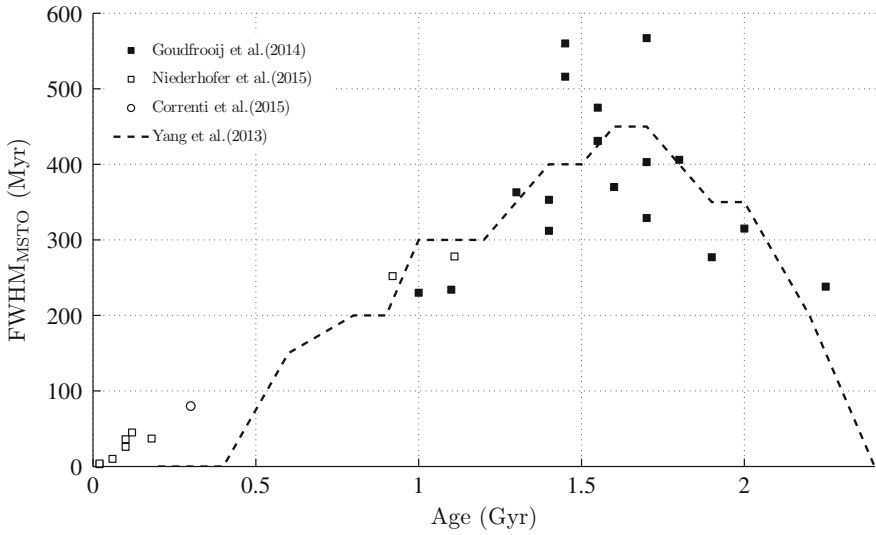


Fig. 2.3 Widths of implied cluster age spreads as a function of their isochronal age. *Black dashed line* Predicted FWHM of cluster age spreads that would be derived from their eMSTO regions as a function of cluster age. *Filled squares, open squares, and an open circle* are the data from [99, 109, 110], respectively

Stars with different rotational rates would be mainly affected by different effects, a stellar population composed of extremely fast rotators may be mainly affected by gravity darkening, while a stellar population only contains relatively moderate rotators may more prefer to be affected by rotational mixing. In stellar evolutionary model, the stellar rotational rate can be described by $\Omega/\Omega_{\text{crit}}$, where Ω is the stellar angular rotation rate and Ω_{crit} is the critical, ‘break-up’ value. To illustrate this difference, in Fig. 2.4 we present synthetic HRD of SSPs with $\Omega/\Omega_{\text{crit}} \leq 0.5$ (left panel) and $\Omega/\Omega_{\text{crit}} \geq 0.5$ (right panel) for an age of 1 Gyr and a metallicity of $Z = 0.006$, which is roughly the typical value of most intermediate-age LMC and SMC star clusters. Figure 2.4 shows that for stars with their rotational rates span from $\Omega/\Omega_{\text{crit}} = 0$ to 0.95, the SGB also spans in a large range of magnitude; while for those extremely fast-rotating stars (left panel, $\Omega/\Omega_{\text{crit}} \geq 0.5$), the SGB is well populated with very small magnitude dispersions.

Analyses on the SGBs of SCs who harbor eMSTO were carried out recently. As introduced, so far there were already four SCs, NGC 411 [75], NGC 1651 [72], NGC 1806 and NGC 1846 [73], seem harbor their SGBs that are inconsistent with an dramatic age spread (however, see [74]). A more exciting result appears soon, Wu et al. [112] found for SMC cluster NGC 419, its CMD shows apparent ‘converging’ in the SGB, i.e., the SGB seems wide in blue range while narrow in red range, the only explanation to this feature is these SGB stars are slowing down, i.e., the more evolved SGB stars have lower rotational rates than these less evolved SGB stars. All these results may suggest that the gravity darkening in these clusters is more important than

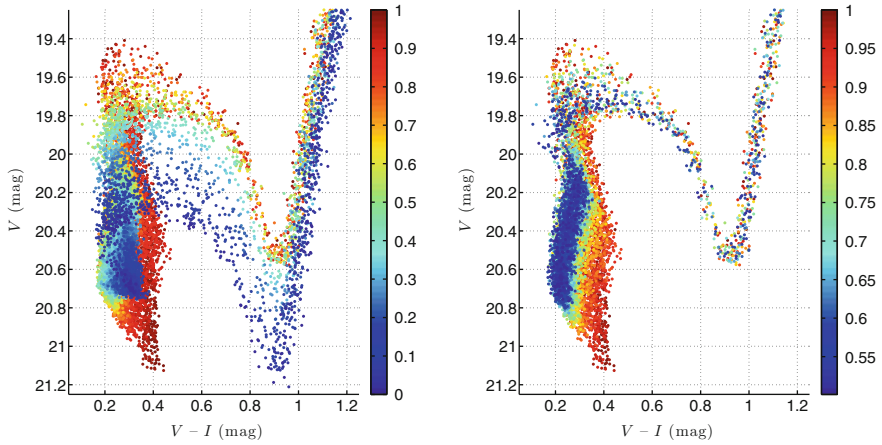


Fig. 2.4 Synthetic $(V, V - I)$ CMD for a coeval stellar population with an age of 1 Gyr and a metallicity of $Z = 0.006$, for stars with initial rotation rates of (left) $\Omega/\Omega_{\text{crit}} \leq 0.95$ and (right) $\Omega/\Omega_{\text{crit}} \geq 0.5$. The color bars indicate the initial stellar rotation rates. Calculated through Geneva stellar evolutionary model [111]

rotational mixing effect, based on Fig. 2.4, if the Geneva stellar evolutionary model is correct, then it may further indicate that most stars in these SCs are extremely fast rotators.

The discovery of eMSTOs in YMCs seems confirm this speculation: the eMSTO of NGC 1856, a 150 Myr-old YMC in LMC, suggests a possibly ~ 80 Myr age spread, if assume this eMSTO is produced by stellar fast rotating rather than an age spread, then its stellar population should be composed by a combination of two-third rapidly rotating stars and one-third slowly/non-rotating stars [110]. Same conclusion was also reached in another YMC NGC 1755, which displays a split main sequence that favors the variable stellar rotation scenario rather than an age spread [113]

In summary, the apparent eMSTO regions in intermediate-age SCs and YMCs in the LMC and SMC can be explained by either an age spread scenario or rapid stellar rotation scenario. The discussions on the origin of eMSTO regions are still ongoing.

2.2.2 Multiple Stellar Populations in Old Globular Clusters

The presence of MSPs in old GCs is undoubted, but their origin remains unclear, so far almost all proposed scenarios that aim to explain the formation of MSPs in GCs can be classified into two categories. The first type of hypothesis suggests a primordial origin, in the sense that GCs may have been born with chemical inhomogeneities. The second type of scenario insists the SSP origin for GCs, which claims that the MSPs in GCs are the result of stellar evolution [114].

Most primordial scenarios invoke self-pollution of intra-cluster gas during the early stages of cluster evolution, possible polluters during that stage include the ejecta of rapidly rotating massive stars [32], massive binaries [115], or evolved post-giant-branch stars [116]. Another scenario divides GCs into three populations, GCs with initial masses $\geq 10^9 M_\odot$ can retain the ejecta of all types of massive stars, including those of their core-collapse supernovae. The relatively less massive GCs, with masses of several $10^8 M_\odot$ would only be able to keep a fraction of the fast winds from massive stars. The least massive GCs would not be able to capture any gas ejected by massive stars, they could only form new stars from the slow winds of intermediate-mass stars of the first stellar population [117]. A more recent scenario suggests that a temporal sequence of AGB populations may be able to explain the observed MSPs in GCs: such a pollution process occurs after the period of Type II supernovae, lasting until the third dredge-up associated with the AGB population. In this scenario, the cluster-to-cluster abundance variations is ascribed to the differences of many processes and gas sources which were involved in the formation of the secondary generation [118]. If this scenario was on the right track, then a GC should be able to keep its mass that is 100 times more massive than its current mass after the Type II supernovae epoch (~ 20 Myr), otherwise the self-pollution scenario would be failed to explain the high fraction of the observed secondary stellar populations in most GCs. However, another study have revealed an intrinsic problem among all self-enrichment scenarios that they are unable to produce consistent abundance trends among He, Na and O [119]. While all these self-cycle scenarios have predicted a extremely massive origin for GCs who have MSPs, however, current investigations have shown that clusters are almost gas-free at a very early stage (2–3 Myr), independent of their mass [120, 121], which indeed show that clusters may not be able to retain their initial gas during the initial gas-expulsion phase, but this does not prevent a cluster from accreting external gas onto its central region when moving through a background medium [122].

Another primordial formation scenario invokes the cluster merger, an advantage of this hierarchical formation scenario is that it does not require a extremely massive origin for individual clusters, thus solves the ‘initial exhaustion’ problem. Cluster members in crowded environments are easy to frequently collide and merge [123], resulting a stellar system contains more than one stellar populations. However, this scenario may preferentially favors clusters in crowded environments (e.g., cluster pairs in the Antennae interacting system [124]), while most GCs in our Milky Way are located in the Galactic halo, where frequent mergers are not expected to occur.

The evolutionary scenario treat the star-to-star abundance variations in GCs as the result of dredge-up of material that has been processed through the CNO cycle in the stars themselves. Because the observed elemental chemical dispersions in GC stars only reflect variations in their surface abundances, any process that would change the chemical compositions of stellar surfaces would produce a star-by-star variation in their elemental abundances. Lots of mechanisms that may affect the mixing of stellar material have been proposed. Some of them seem auspicious indeed, for example, a study had had shown that the significance of Na–O anticorrelation of GGCs is depend on their RGB luminosity [125], indicating this correlation may be affected by internal deep mixing of evolved stars during their ascent of the RGB, thus partially

support the evolutionary scenario. Another possible mechanism that may lead stars to undergo deep mixing invokes the stellar magnetic fields: Nucci and Buso [126] proposed a scenario involving the advection of thermonuclear ashes by magnetized domains emerging near the H shell to explain AGB-star abundances, confirming that the stellar-envelope crossing times are able to facilitate chemical dispersion in a huge convective shell, the stellar deep mixing induced by the magnetic advection may explain the observed abundance anomalies in GCs.

However, a key problem of the evolutionary scenario is that stars in GCs are usually late-G- or K-type stars, their central temperatures are not sufficient high to produce the observed Na–O anticorrelation. A possible solution to this problem invokes the binary merger, as binary stars usually occupy a considerable fraction in a stellar population, their mergers will produce a large number of zero-age massive stars, the BSSs. BSSs may be initially fast rotators, they may experience sufficient convective mixing, thus produce a star-to-star surface chemical dispersion once evolve to RGB phase. Such a model based on fast rotators that are produced by binary mergers or interactions have been confirmed to be able to produce a Na–O anticorrelation with high significance [127]. Clearly, this scenario strongly depend on the binary fraction of SCs, actually, it depends on how many binaries can be eventually evolve to interactive phases. It seems that more than half of objects in YMCs are actually binaries (at least for stars that earlier than F-type) ([69, 128, 129], also will be introduced in Chap. 3), this seems also hold for some OCs, Mathieu and Geller (2009) [130] have found that the population of BSSs in OC NGC 188 contains 76% binary systems, which confirms the close relationship between binary stars and BSSs. To test the evolutionary scenario, a promising approach is to study the elemental dispersion of BSSs in SCs, which may improve our understanding of the origin of MSPs in GCs.

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