

# Evaluating Helium Variations By Modeling Red Giant Branch Bump of Large Magellanic Cluster NGC 1978

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## Abstract

Many evidences show that the Multiple Population (MP) features exist not only in old clusters but also in intermediate-age clusters in the Megallanic Clouds (MCs), which are characterized by star-to-star abundance scatter of several elements, including helium (He). The red giant branch bump (RGBB)'s photometric properties are proved to be related to the variation in helium abundances of the member stars in star clusters. We use the "Modules for Experiments in Stellar Astrophysics" (MESA) stellar evolution code to calculate the evolution sequences of stars along the red giant branch (RGB) with changing helium content. Following the RGB sequences, we then generate a luminosity function of the RGB stars within the grid of input helium abundances, which are compared with the observational data of an intermediate-age MC cluster NGC 1978.

*Key words:* globular clusters: general – globular clusters: individual (NGC 1978) – stars: abundances – stars: Hertzsprung–Russell and C–M diagrams – stars: luminosity function

## 1. Introduction

Star clusters were thought to be the basic units of star formation (Lada & Lada 2003): almost all stars originate from a common progenitor giant molecular cloud (GMC) during the same era and sharing similar metallicities, which advises a "simple stellar population" (SSP) scenario. In this scenario, star cluster should form in a single-burst mode as the star formation process in a star cluster will cease rapidly after formation of the first-generation stars owing to the quick exhaustion of the initial gas, which is mainly caused by stellar wind-induced mass loss (e.g., energetic photons ejected by the most massive stars, Long et al. 2014) and supernova explosions. The timescale of gas expulsion driven by these initial stellar winds is very short, usually less than or comparable to the cluster's crossing time ( $\sim$ 1 Myr). Later at about 30 Myr, lower mass stars will undergo the post-RGB and asymptotic giant branch (AGB) phases, ejecting stellar material into the interstellar medium, which might be a possible origin of the second generation. But it is not easy for an evolved cluster to retain the gas. Combining these scenarios, calculations and observations give that open clusters (OCs) and young massive clusters (YMCs) will lose their initial gas in the early evolution phases, while only small part of the OCs can retain the gas in both cases. In a word, clusters should be well represented by the SSP scenario, as proven by numerous previous studies (Baumgardt & Kroupa 2007; Lima et al. 2014; Cabrera-Ziri et al. 2015; Farias et al. 2015).

Thanks to advances in observational techniques, especially after the launch of the Hubble Space Telescope (HST), the multiple population was found as a common feature in lots of globular clusters. The cluster may be consist of groups of stars with different ages and chemical elements, such as He, C, N, O, Na, Mg, Al, or even Fe. These facts directly imply that many globular clusters are not just composed of a group of stars formed at the same time and environment, but more than one generations of stars in different backgrounds.

Stars with more than one generations mean that some stars may be formed later than the bulk formation in the environment that contains the residual materials of earlier stars, mainly the massive and intermediate-mass ones. As those stars have already undergone the hydrogen burning (CNO cycle, in specific), the building material for the later formed stars will be different in chemical abundance from the major population. The main signature are: (1) Helium. As the production of hydrogen burning, helium will be enriched by the earlier generations, thus the initial He abundance of later generations will be enriched as well; (2) Carbon, nitrogen and oxygen. Although these elements are thought to be "catalyst" during the CNO cycle, the specific reactions in the cycle have different rates (especially for the proton capture on <sup>14</sup>N, which is the slowest one). As a result, the N abundance will be enhanced at the expenses of lowering of C and O; (3) Some other protoncapture like Ne-Na and Mg-Al chains also occur during hydrogen burning at high temperature, which affect the abundance of these elements (enrich the Na and Al while deplete the Mg, and in turn



Figure 1. Spatial distributions of stars in NGC 1978 field. Stars within the adopted cluster region (black), reference field stars (red), and number density contours are colored and shown.

lead to the well-known Na-O and Mg-Al anti-correlation) (Shetrone 1996; Gratton et al. 2004; Carretta et al. 2009). Those elementary variations were observed in a large number of globular clusters. A famous example is NGC 2808, which was first detected to have triple main sequence in colour-magnitude diagram (CMD) with different He abundance (Piotto et al. 2007). Also another photometric technique was used for detecting multiple populations in globular clusters. An effective method is using the "magic trio" of the HST filters, which means a combination of three HST filters. In details, the HST UVIS/WFC3 F275W passband includes an OH molecular band, while F336W an NH band, and F438W (or F435W for Advanced Camera for Surveys(ACS) CN and CH bands. Therefore, early generation stars which are O-rich and C-rich but N-poor, are relatively bright in F336W but are fainter than 2Gstars in F275W and F438W, while later generation stars are opposite. CMD's with these filters can be used for recognizing different populations. Specially, the pseudo-color  $C_{\text{F275W,F336W,F438W}} = (m_{\text{F275W}} - m_{\text{F336W}}) - (m_{\text{F336W}} - m_{\text{F438W}})$ defined in Milone et al. (2015) can maximizes the virtue of both F336W-F438W and F275W-F336W, and has proven to be quite efficient in the separation of multiple sequences and was widely used in lots of clusters (Piotto et al. 2015).

This method can be further improved, as Milone et al. (2015) also defined a pseudo two-color diagram of main sequence (MS), red giant branch (RGB), or AGB stars based on photometry in different filters, called the chromosome map (ChM). This technique is quite sensitive to the specific

chemical composition of globular clusters (GCs), For example, ChMs for RGB and MS stars of NGC 2808 constructed by plotting the pseudo-color  $C_{F275W,F336W,F438W}$ , which is mostly sensitive to the nitrogen abundance of MPs, against  $m_{F275W} - m_{F336W}$ , has been used to detected five different populations (Milone et al. 2015). Nowadays it is widely used for the study of the chemical properties of stellar multiple populations in large samples of globular clusters (Milone et al. 2017).

Although helium is the direct product of hydrogen burning, a direct measurement of He abundance is difficult. For old GCs, only a limited number of horizontal branch (HB) stars with effective temperatures ( $T_{\rm eff}$ ), ranging from ~8000 to 11500 K, can be used for direct helium determination (e.g., Villanova et al. 2009; Marino et al. 2014). Deep photometry provides an alternative for the study of stellar He distribution in star clusters. As different initial helium abundances would lead to different stellar nuclear reaction rates, and then change the evolutionary tracks. All these effects affect the morphologies of different parts in a clusters CMD, such as the MSs (e.g., NGC 2808,  $\omega$  Cen; Piotto et al. 2007; Bellini et al. 2010), the redgiant branch bump (RGBB) (Milone et al. 2012; Dalessandro et al. 2013).

The helium abundance measured from the HB stars are usually overestimated due to the evidence that the second generation (2G) stars lose more mass than the 1G (Tailo et al. 2020). Studying the helium distribution based on the MS width turns out to be a more reliable approach where the mass loss is not an issue. However, this relies on ultra-deep photometry that is otherwise not always available. (Li 2021) A compromise is thus to use the RGBB stars. The RGBB appears as a bump (or say, an excess in numbers) on the luminosity function of the RGB stars in the CMD of the cluster. (Thomas 1967; Iben 1968). During the first ascent of the red-giant phase, when the hydrogen-burning shell moves outward, stars become temporarily fainter before becoming brighter again. This is because of a chemical (hydrogen content) discontinuity left behind by the first dredge up in the stellar chemical abundance profile at the bottom of the convective envelope. Because the initial He abundance will affect the depth of the convective envelope at the completion of the dredge up, H-burning shell will encounter the H-discontinuity at different stellar radii, changing the brightness of RGBB (Cassisi et al. 2016).

Apart from the multiple populations on old clusters, several works in recent years were dedicated to the study of MPs in the Magellanic Cloud GCs, in order to check if these intermediateage clusters are the counterparts of Galactic GCs in terms of MPs. Several studies based on the magic trio filters were done, such as NGC 121 (Dalessandro et al. 2016; Niederhofer et al. 2017a), NGC 339, NGC 416 (Niederhofer et al. 2017b), Lindsay 1 (Saracino et al. 2019, 2020a), NGC 1783, NGC 2121 (Saracino et al. 2020a) and NGC 1978 (Martocchia et al.



Figure 2. The procedure of gaining the "decontaminated" LF of cluster area of NGC 1978. The left panel is the raw CMD of cluster, with RGB candidate stars (red dots) selected by the black polygon. Middle panel is the corresponding CMD of the reference field. The RGB stars in the field are selected and marked in the same way as the left panel. The right panel is the LF of the cluster along the RGB. The LF of the total RGB stars on the left panel are marked by blue, while red-dashed is the LF after statistically decontamination. The red shadow indicate RGBB region on RGB.

2018a). In addition, determinations of helium abundance of MC clusters have also been done very recently, by using RGBB combining with ChM and spectra synthesizing, and also modeling the red clump (or HB), with only small helium abundance spread found in some of the clusters (Lagioia et al. 2019; Chantereau et al. 2019).

This work is aimed at the study of the variation of He content among stars in intermediate-age clusters in the Magellanic Clouds. We are concentrated on a specific target, NGC 1978, which has been confirmed to have MPs (Martocchia et al. 2018a; Saracino et al. 2020b; Li et al. 2021). The method adopted here is to model the RGBB via MESA stellar evolution code. By building up a grid of evolutionary sequences of different He abundances, we can pick up the RGBB phases on the tracks, which can be then analysis by the synthetic RGB luminosity functions (LFs). Finally we will use a chi-squared test between the models and the observation cluster RGBs, and in turn to link the He abundance variations and the RGBB pattern of the cluster.

## 2. Observations and Data Analysis

We use high-resolution data collected through the Wide Field Channel of the Advanced Camera for Surveys (ACS/WFC) on board of the Hubble Space Telescope (HST, GO-9891 program, PI: G, Gilmore). The photometry data of NGC 1978 was processed using the DOLPHOT<sup>5</sup> stellar photometry package with its ACS module. We ran the *acsmask*, *splitgroups*, *calcsky*, and *dolphot* tasks in order, following the preprocessing steps recommended in the *DOLPHOT/ACS* Users Guide to obtain the best photometric results. DOLPHOT

output files include several parameters to estimate the quality of our photometry: *Signal-to-noise*, *Object sharpness*, *Object roundness*, *Crowding*, *Object type* and *Magnitude uncertainty*. In our research we choose stars with |Object sharpness| < 0.1, *Crowding* < 0.7 mag and *Magnitude uncertainty* < 0.2 mag to select photometric data which have high enough quality for our research (Monelli et al. 2010), especially for RGBB stars.

The next step is to make corrections for the field-star contaminations of the RGB in a statistical way. We first define the appropriate cluster and reference fields, by simply assigning the coordinate where the number density reaches the peak value as the cluster center (which is at the pixel of x = 2070.05, y = 3101.53, whose corresponding coordinates are  $\alpha_{J2000} = 5^{h}28^{m}44^{\$}.79$ ,  $\delta_{J2000} = -66^{\circ}14'12''.30$ , which are in good agreement with the coordinates  $\alpha_{J2000} = 5^{h}28^{m}45^{\$}.33$ ,  $\delta_{J2000} = -66^{\circ}14'12''.04$  listed by the Strasbourg Astronomical Data Centers SIMBAD database<sup>6</sup>), and then we choose a radius where the number density just becomes flat at the level of the surrounding field. The reference field of NGC 1978 located at the edge of the images is shown in Figure 1.

After that we plot the CMD of the cluster region and focus on the RGB branch. We also plot the CMD of the stars in the reference field and choose the same CMD area as the cluster RGB, which we define as "field RGB". We then plot the luminosity histogram (or luminosity function, LF) of both the cluster RGB and field RGB, with same number of bins. For each bin, we extract an area-corrected number of the field RGB stars from the corresponding bin of the cluster RGB. Then we can derive the number of stars in this bin that are pure cluster stars in a statistical sense. The same process is repeated for

<sup>&</sup>lt;sup>5</sup> DOLPHOT is a stellar photometry package adapted from HSTphot for general use. See http://americano.dolphinsim.com/dolphot for more information.

<sup>&</sup>lt;sup>6</sup> http://simbad.u-strasbg.fr/simbad/

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Table 1
Input Physics for Modeling, Mainly from Choi et al. (2016). Some parameters like $\alpha_{MLT}$ are modified for our modeling

Ingredient	Adopted Prescriptions and Parameters	
Equation of state	OPAL+SCVH+MacDonald+HELM+PC	
Opacity	OPAL Type I for log $T \gtrsim 4$ ; Ferguson for log $T \lesssim 4$ ;	
	Type I $\rightarrow$ Type II at the end of H burning	
Reaction Rates	JINA REACLIB	
Boundary Conditions	ATLAS12; $\tau = 100$ tables + photosphere tables + gray atmosphere	
Diffusion	Track five "classes" of species; MS only	
Radiation Turbulence	$D_{\rm RT} = 1$	
Rotation	solid-body rotation at ZAMS with $v_{ZAMS}/v_{crit} = \Omega_{ZAMS}/\Omega_{crit} = 0.4$	
Convection: Ledoux + MLT	$\alpha_{\rm MLT} = 2.12, \ \nu = 1/3, \ y = 8$	
Overshoot	time-dependent, diffusive, $f_{ov,core} = 0.0160$ , $f_{ov,env} = f_{ov,sh} = 0.0174$	
Semiconvection	$lpha_{ m sc}=0.1$	
Thermohaline	$\alpha_{\rm th} = 666$	
Mass Loss: Low Mass Stars	$\dot{M}_{\rm R} = 4 \times 10^{-13} \eta_{\rm R} \frac{(L/L_{\odot})(R/R_{\odot})}{M/M_{\odot}} M_{\odot} {\rm yr}^{-1};  \eta_{\rm R} = 0.1$ for the RGB	
Mass Loss: Rotational	$\xi = 0.43$ , boost factor capped at $10^4$ , $\dot{M}_{max} = 10^{-3} M_{\odot} v r^{-1}$	



Figure 3. Isochrone fitting of NGC 1978. Fitted parameters are described in the article.

every bin, and finally we get the LF of the cluster, which is free of field contamination, as shown in Figure 2.

To understand how chemical composition acts in the course of stellar evolution, we computed stellar evolution sequences with MESA (Modules for Experiments in Stellar Astrophysics). MESA is an open-source stellar evolution package that is undergoing active development thanks to the huge community. The one-dimensional stellar evolution module (MESAstar) which has been thoroughly tested against several existing stellar evolution codes and databases, therefore it can provide comprehensive and up to date modeling of single stars. With its flexible infrastructure and its robust numerical methods we can do a wide range of work in computational stellar astrophysics, like asteroseismology, helium core flash in low-mass stars, as well as the evolution of giant planets, accreting white dwarfs (WD), and binary stars, etc.

In our modeling, we mainly use the input physics as described in Choi et al. (2016), with some minor changes for immediate calculations, as shown in Table 1. To model the RGBB properties in the context of multi-generations (variations in chemical composition) of the clusters, we need to determine the initial metallicities (Z) of stars and the mass range corresponding to the clusters under consideration. These parameters come from the isochrone fitting (by using the Padova PARSEC models (Bressan et al. 2012). The fitting is demonstrated in Figure 3, with chosen parameters of lgAge = 9.42, Z = 0.008, distance modulus DM = 18.50 mag, and extinction value  $A_V = 0.10$  mag, which are close to those of Martocchia et al. 2018b). In observations, the RGB on a CMD of a real cluster is populated by stars with a very narrow range of masses due to the short lifetimes of RGB phase of evolution compared with that of the MS lifetimes of the stars. For this reason, the RGB sequence can be well represented by a single mass stellar evolutionary track, and the mass is very close to the mass of stars at the turn-off point of the cluster, or any mass determined from isochrone fitting to RGB. In this work, we pick up the points from the fitted isochrone near the position of RGBB on the CMD, for the specific case of NGC 1978, the initial mass of them is 1.46  $M_{\odot}$ . Given the initial parameters, we run the MESA code, and look for the evolutionary track that best fits the RGB of the cluster. While running directly with the



NGC 1978, Z=0.008, α<sub>MLT</sub>=2.12

Figure 4. CMD of the models that we run near the RGB branch. Near observations are also plotted.



Figure 5. F555W against star\_age plot of modeled RGB branch of NGC 1978. He abundance of each model is shown in the label. The grey shadow roughly indicates the range of RGBB on each model.

MIST parameters, we found that most of the evolution tracks are redder than observation on RGB branch, which indicate that some parameters from Choi et al. (2016), like the convection parameter ( $\alpha_{MLT}$ ), do not really fit NGC 1978. To solve this problem, we change the He abundance and the  $\alpha_{MLT}$ 

simultaneously and try out all these parameter combinations to find the sequence that fits the observed RGB best (specifically we need to convert the results into ACS/WFC filters and calculate the  $\chi^2$ , more details are described below). Finally we got the best fitted model, with Y = 0.251 and  $\alpha_{\text{MLT}} = 2.12$  (as shown in Table 1).

With all the prescriptions in position, we computed a series of models that have Helium abundances roughly centered at Y = 0.251 (as Figure 4 shows, we select more models near the best fitting). A grid of evolutionary models with only changing Helium abundance Y from protostar until the onset of the core He-burning phase. The result evolution tracks are stored in the history files, including star\_age, star\_mass, log\_L, log\_Teff, log\_g columns, etc. We convert the log\_L and log\_Teff into the ACS/WFC filters mag using the PARSEC Bolometric Correction (Chen et al. 2019). Given the HST/ACS magnitudes of our result models, we plot the F555W mag against star\_age, as shown in Figure 5, from which we can evaluate the time spent in the RGBB phase of each sequence. It is straightforward to learn that the longer time the star spends near a position in CMD, the more stars we will see at that position. Statistically, we will get the stellar magnitude distribution on the RGB branch of the cluster, which is actually the luminosity function (LF) we wanted to look for at the first place. As we can see from Figure 5, the lower the



Figure 6. Result  $\chi^2$  of different composed models with different  $\sigma$ (He), obvious minima below 0.3 put a constraint on the spread in Y.

helium abundance, the longer time will be spent on the RGBB region (the gray shadowed area), however the RGBB will also be more spread on the CMD (see Figure 4)), which means that for lower helium abundance the RGBB is less apparent. In fact, lower helium abundance than that of the best fit of the cluster is in conflict with the current picture of chemical enrichment. Inclusion of low helium models is a theoretical extrapolation, which is useful only for the study of possible spread in *Y*.

Having a series of evolutionary sequences with different He abundances, we can now proceed to measure the possible spread of helium content in member stars of NGC 1978. Due to faster evolution of stars with mass higher than MS-turnoff, and the corresponding gas recycling process before the final extinguishing of star formation in the cluster, the stars in a cluster may bare a helium spread ( $\Delta Y$ ) if they were not forming at the same time. In order to fit our models to observations, we choose a number of the models with different helium abundances and assign them with weights that follow a Gaussian distribution, centered at the best fit helium abundance of the cluster, with a given  $\sigma$ . This fitting process is repeatedly done for a series of  $\sigma$ , and each time an LF is derived with given  $\sigma$ .

Each of the resulted LFs is further compared to the observed LF of NGC1978 by a  $\chi^2$  technique. We simulated the distribution of each fitted LFs by fixing the observed number of RGB stars. By further sampling the RGB stars' F555W magnitudes with the same number of bins as of the observed data, then the  $\chi^2$  for each fit can be calculated. To emphasize the effect of the RGBB stars, higher weights of the bins just covering the observed RGBB luminosity range are used, which is expressed in the following,

$$\chi^2 = \sum_{i} \frac{w_i (x_{i,\text{model}} - x_{i,\text{observed}})^2}{x_{i,\text{observed}}} \tag{1}$$

Here  $w_i$  is the weight we use while calculating the  $\chi^2$ . We choose  $w_i = 2$  near the RGBB and  $w_i = 1$  for the other parts. *i* varies from 1 to the number of the bins of the LFs, which is 30 in specific, and same as the observed LF we use. The RGBB part we choose are shown as red shadow in the right-hand side

panel of Figure 2. For each composed model with given  $\sigma$  we redo these steps for 10 times and take the mean  $\chi^2$  as the final one of this model. Finally as we get the  $\chi^2$  for all the composed model, from which we will choose the one with the lowest  $\chi^2$ , and take a proper *n*, let  $\Delta Y = n\sigma$  be our final estimated result of He variation.

#### 3. Results and Discussion

We composed several models with a series of stellar evolution tracks with different He abundance centered at our best-fitting model with different  $\sigma$ , and calculated the  $\chi^2$ between the LFs along the RGB branch of our models and the observation. The  $\chi^2$  calculation is modified by adding the weight of RGBB stars, in order to emphasize there effects, as Equation (1) shows. We did not use isochrone models to fit and calculate the  $\chi^2$ , because evolution tracks with different parameters are easier to get, and are already good enough for our calculation. Since all the stars we use and model here are positioned on the RGB branch, and along the RGB branch, star evolution is rapid enough, which cause the star mass does not change a lot along the RGB (for NGC 1978 the maximum mass difference along the RGB is less than 0.02  $M_{\odot}$  from the isochrone fitting), the influences of mass on RGB are almost ignorable compared with those effects by stars' lifetime. Thus evolution track is suitable to be used instead of isochrone, and can be used as the clusters' RGB model, as we have already done in Section 2. After the composing the models and processing the chi-squared test, we get a series of  $\chi^2$  of different composed models with different  $\sigma$ , as shown in Figure 6,

In the  $\chi^2 - \sigma$  figure, we found the result comes with a nonnegligible noise level, which is mainly caused by the simulated RGB, whose stars are randomly chosen from the LF models. However we can still notice that the  $\chi^2$  of those points below the red-dashed lines look significantly below the noise level of other points, which suggests that the He spread should below ~0.03 (as the vertical dashed line shows). But it is still hard to get a lower limit, as NGC 1978 is massive enough to possess a more detectable He spread. Figure 7 plots maximum  $\Delta Y$ 



**Figure 7.** Relation between the maximum helium spread  $\Delta Y$  and cluster total masses. Blue circles shows six SMC clusters from Chantereau et al. (2019, C19), with four of them also studied by Lagioia et al. (2019, L19). Each of the corresponding  $\Delta Y$ s from the two studies are paired by a blue bar. Black dots are Galactic GCs results from Milone et al. (2018, M18). The green circle is NGC 1846 from Li (2021b, L21) and the red square indicates NGC 1978 in this work.

against cluster total masses of NGC 1978 (data from Li et al. 2021) along with other clusters, which suggests that NGC 1978 fits well the correlation in previous studies. Previous work (Chantereau et al. 2019) suggested an upper limit  $\Delta Y_{\rm max} \sim 0.04$ , which is larger than that of ours. This may be caused by the fact that more mass loss in the advanced stages of evolution, such as the HB phase, was used while the effects of mass loss were not taken into account (e.g., Tailo et al. 2020). To this respect, using RGBB as a probe for helium spread should be more realistic than using HB, as the issue of mass loss in RGBB stars is much less than that in HB stars. Therefore, the abundance spread should have more significant influence on luminosities of RGBB stars than that of the HB stars. The green circle in Figure 7 may support such an argument even better, as its He spread is studied by MS stars (Li 2021), whose mass loss should be even less than RGBB ones.

#### 4. Summary and Conclusions

- 1. NGC 1978 has a small helium spread (with  $\Delta Y < 0.03$ ), or it is a cluster with virtually a single population judged from the properties of RGBB stars.
- 2. The estimated  $\Delta Y$  for NGC 1978 is in consistent with the correlation between the maximum helium spread and the clusters total masses derived for Galactic GCs.

It is concluded that, to achieve reliable assessments of helium abundance distribution and then to understand the origins of MPs in massive clusters, a better probe is looking into the MS dwarf content. Accurate and ultra-deep photometry, or preferably high resolution spectroscopy is required. Future space program, such as CSST with UV coverage is very promising in the subject of the current study.

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