Multiple Stellar Populations at Less-evolved Stages: Detection of Chemical Variations among Main-sequence Dwarfs in NGC 1978

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Abstract

Multiple stellar populations (MPs) with different chemical compositions are not exclusive features of old globular clusters (older than 10 Gyr). Indeed, recent studies reveal that younger clusters (~2–6 Gyr-old) in the Magellanic Clouds also exhibit star-to-star chemical variations among evolved stars. However, whether MPs are present among less-evolved dwarfs of these intermediate-age clusters is still unclear. In this work, we search for chemical variations among GK-type dwarfs in the ~2 Gyr old cluster NGC 1978, which is the youngest cluster with MPs. We exploit deep ultraviolet and visual observations from the Hubble Space Telescope to constrain the nitrogen (N) and oxygen (O) variations among main-sequence (MS) stars. To do this, we compare appropriate photometric diagrams that are sensitive to N and O with synthetic diagrams of simple stellar populations and MPs. We conclude that the G- and K-type MS stars in NGC 1978 host MPs. Our statistical analysis shows that the fraction of N-rich stars ranges from ~40% to ~80%, depending on the detailed distributions of N and O.

Unified Astronomy Thesaurus concepts: Stellar populations (1622); Star clusters (1567); Large Magellanic Cloud (903); Hertzsprung–Russell diagram (725); G dwarf stars (556); M dwarf stars (982)

Supporting material: data behind figure

1. Introduction

Chemical variations among member stars of star clusters, which imply the presence of multiple stellar populations (MPs), are detected in intermediate-age (~2–6 Gyr old) Magellanic Cloud clusters (Martocchia et al. 2017; Milone et al. 2020). These findings expand the phenomenon of MPs to star clusters spanning a more extensive age range (Martocchia et al. 2018; Li & de Grijs 2019). Like most old globular clusters (GCs), these intermediate-age clusters in the Magellanic Clouds exhibit clear signatures of chemical variations in He, C, N, and O among their evolved stars (e.g., Milone et al. 2020). Once MPs appear in star clusters, they seem to follow the same correlation between the number fractions and the host cluster masses, regardless of their age and the nature of their parent galaxy (Milone et al. 2020).

For Galactic GCs (GGCs), MPs are suggested to have a primordial origin. Intermediate-age asymptotic giant branch (AGB) stars (D’Ercole et al. 2010; D’Antona et al. 2016), fast-rotating massive main-sequence (MS) stars (Decressin et al. 2007), massive interacting binaries (de Mink et al. 2009), or just a single supermassive MS star (Denissenkov & Hartwick 2014), and their combination may play a role as polluters of second-generation (SG) stars (Wang et al. 2020). MPs are known as a global feature for stellar populations at different evolutionary stages in GCs. Most works focus on MPs among bright giant stars since they are the most luminous sources in most GCs (e.g., Yong et al. 2008; Tang et al. 2017; Wang et al. 2017; Lee 2019). For GGCs, observations also provide substantial evidence which supports the presence of MPs among less-evolved stars, such as MS stars or sub-giant branch stars (e.g., Lardo et al. 2012). MPs are found among the bottom-MS stars (~0.15 M⊙) when photometry with deep exposures is involved (Milone et al. 2019). These findings rule out the possibility that MPs can form through standard stellar evolutionary processes such as evolutionary mixing (Denisenkov & Denisenkova 1990).

As discussed, understanding whether MPs have a primordial or an evolutionary origin is crucial to constraining their formation mechanisms. For most Galactic open clusters, their photometry is strongly hampered by the large reddening caused by dust in the Galactic disk. This makes massive clusters in the Magellanic Clouds better targets. However, because of the large distance, whether the less-evolved dwarfs in the Magellanic Clouds clusters could harbor MPs is yet to be examined. It remains unclear if the MPs in Magellanic Cloud clusters could have the same origin as those in GGCs. Thanks to ultra-deep exposures in ultraviolet (UV) and optical passbands with the Hubble Space Telescope (HST), some indirect evaluations of chemical spreads among MS stars in the Magellanic Clouds have become feasible. Based on UV– optical frames with deep exposures, the Small Magellanic Cloud cluster NGC 419 (~1.4 Gyr old) is proved to have no signature of MPs among its MS stars (Cabrera-Ziri et al. 2020;
Li et al. 2020). But this does not lead to the conclusion that the origin of MPs in Magellanic Cloud clusters is different from that in GCs, because NGC 419 does not exhibit any feature of MPs in its red-giant branch (RGB; Martocchia et al. 2017) either, making it a genuine simple stellar population (SSP) cluster. A similar study of the RGB of the cluster NGC 1783 was performed by Zhang et al. (2018), who reported no evidence of chemical variations among these evolved giants. These clusters seem to define a minimum age limit for MP clusters (~2 Gyr; Martocchia et al. 2018). Indeed, we have SSP GCs older than 2 Gyr but no MP GCs younger than 2 Gyr.

For clusters older than this age limit, NGC 1978 is one of the youngest clusters (~2.3 Gyr) known to have MPs: studies have reported the presence of internal chemical variations of carbon, nitrogen, and oxygen, with a nitrogen variation of up to Δ[N/Fe] = 0.5 dex (Martocchia et al. 2018), and a negligible helium spread (ΔY = 0.002 dex; Milone et al. 2020). All these conclusions were drawn based on analyses of RGB stars. It is, therefore, necessary to examine if its less-evolved dwarfs could exhibit a similar feature of MPs. In this work, based on the depth of the observations, we used a similar method as in Li et al. (2020) to examine if NGC 1978 could exhibit a signature of MPs among its GK-type MS stars.

In this paper, the data reduction is discussed in Section 2. The methods we use and the main results are presented in Section 3. Our main conclusions are summarized in Section 4.

2. Data Reduction

Our data sets are derived from two observational programs observed through the HST’s Ultraviolet and Visible Channel (CENTER aperture) of the Wide Field Camera 3 (UVIS-CENTER/WFC3); they are programs with an ID of General Observer (GO)-14069 and GO-15630 (PI: N. Bastian). In Table 1, we present the details of the observational frames. The passbands we used in this work include F275W, F343N, F438W, and F814W, with total exposure times of 17,970 s, 3975 s, 2475 s, and 2334 s, respectively.

We perform point-spread-function (PSF)-corrected photometry to the pixel-based charge transfer efficiency-corrected frames (“flc”), using the package DOLPHOT2.0 (Dolphin 2011a, 2011b, 2013). When adding fake stars, Poissonian noise is always applied to their PSFs. The standard data reduction procedures include bad pixel masking, splitting frames based on CCD chips, and background correction. After that we perform the dolphot command to frames belonging to the same observational program. dolphot can automatically read the World Coordinate System (WCS) header information from each frame for alignment, and enable a full stellar catalog including stellar magnitudes in different passbands. From the raw stellar catalog, we remove stars if they have any of the following features. (1) Their stellar magnitude in any passband is 99.99 (flagged by DOLPHOT if these are failed measurement). (2) Their stellar types are not “good star” (flagged by DOLPHOT with a type-ID of 1). (3) They are likely cosmic rays or extended sources with a too low (<0.3) or too high (>0.3) sharpness. (4) Their crowding parameter is too high (≥0.1 mag). Except for the crowding, all other parameters are decided followed by the optimal suggestions from the manual of DOLPHOT2.0 (Dolphin 2013). The crowding tells how much brighter the star would have been measured had nearby stars not been fit simultaneously. Because GK-type dwarfs are usually severely affected by crowding in a cluster, high crowding would hamper the reliability of our results. Under this adoption, we confirmed that even a maximum crowding (0.1 mag) would not exceed 20% of the photometric uncertainty of stars for analysis. The average crowding parameter for our sample stars is only 0.02 mag.

The spatial coordinate of stars in the raw stellar sample is in X and Y, which describes their 2D positions in the CCD. We transferred their CCD positions to J2000 (α2000 and decl. δ2000) using the WCS matrix identified from the header of the reference frames.

At this stage, we will obtain two stellar catalogs, corresponding to two different observational programs, GO-14069 and GO-15630. These two stellar catalogs describe the same cluster NGC 1978 in different passbands (see Table 1). We combined these catalogs through cross-matching their spatial coordinates (α2000 and δ2000). The detection limit (the magnitude where the stellar completeness is ~50%) is determined by the combination of F275W, F343N, F438W, and F814W passband observations. That means if a star is not detected in any one of these passbands, we treat it as a failed detection and it will contribute to the incompleteness. In this work, in order to improve the reliability, we only select stars that are 0.3 mag brighter than the detection limit (GK-type stars). The completeness for our stars of interest ranges from 65.1% to 93.4%, depending on the artificial star (AS) test (introduced below). The average completeness for these stars is greater than 80%.

We first correct the differential reddening, the reddening variation of stars across the entire cluster region, for our sample stars using the same method as Milone et al. (2012). Their method cannot determine the absolute reddening for individual stars. Instead, it would correct stars at different positions to the median reddening value of the whole stellar population. We examine the distribution of differential reddening for stars in NGC 1978 using their (F438W–F814W versus F438W) color–magnitude diagram (CMD). In Figure 1 we show this CMD before/after correcting for differential reddening. We report an average differential reddening degree of δE(B − V) = 0.006 mag, with a maximum value of δE(B − V) = 0.021 mag. From Figure 1 (left panel) we can see that before we correct for differential reddening, stars with large differential reddening show a preferential distribution around the red side of the MS. In the right panel of Figure 1 we confirm that the differential reddening-corrected CMD no longer shows this reddening–color correlation.

As introduced by Milone et al. (2012), in addition to the differential reddening, some unmodelable PSF variations may add additional noise to the observation, leading to color variations for different color baselines. This effect could be very significant for faint stars with low signal-to-noise ratios. We followed the same procedures as Milone et al. (2012) to correct for the variations in F275W–F343N and F343N–F438W, because the color index we used is the combination of these two colors (see Section 3). However, note that even though we have corrected for possible variations in both the directions of reddening and different colors, some statistical residual would still remain.

The field-of-view of our observations is very small. For the combined stellar catalog, the maximum angular radius from the cluster center is only ~2‘/1, or ~30°/2 (pc), which is smaller than the angular size of NGC 1978 (27°–4’0, or 38.9–57.6 pc; Bonatto & Bica 2010). As a result, we are not able to find an appropriate reference field for comparison to estimate the background contamination level. As a second-best choice, we
only select stars that are located within 29\,\arcsec (7.0 pc) (the projected half-light radius, $R_0$; Milone et al. 2020) for our analysis as in this inner region most stars should be cluster members. We select a sample of stars beyond four times the half-light radius ($R \geq 116\,\arcsec$, 28.0 pc) as a reference field to reduce possible field contamination. The field decontamination consists of two steps: we divide the observed color index of both the field and the cluster into several bins (with a bin size of 0.1 mag). Then we randomly subtract the corresponding number of stars in the cluster from the same color index bin (with completeness and area difference corrected). We emphasize that the radius we use for selecting field stars is smaller than the size of NGC 1978. Therefore we may have overestimated the field contamination level.

Finally, the stellar sample we use is the combined stellar catalog with differential reddening, color variations, and field contamination statistically corrected. It includes stars with reliable detections and low sharpness, and crowding, in the F275W, F343N, F438W, and F814W passbands.

### 3. Methods and Results

#### 3.1. Photometric and Spectroscopic Models

In this work, we used the color index

$$C_{F275W,F343N,F438W} = (F275W - F343N) - (F343N - F438W) \quad (1)$$

to reveal the possible presence of MPs along the MS of NGC 1978. For late-type stars, their UV band spectrum ($\leq 300$ nm) contains a lot of OH absorption bands. In the meantime, the NH and CH absorption bands are centered around ~337 nm and ~430 nm, respectively. For GGCs with MPs, a typical feature is that N-enriched population stars would be depleted in O and C. Zennaro et al. (2019) proved that $C_{F275W,F343N,F438W}$ can maximize the separation between the primordial and enriched stellar populations.

We applied the MESA Isochrone and Stellar Tracks (Paxton et al. 2011, 2013, 2015; Choi et al. 2016; Dotter 2016) to find the best-fitting model to the observation. We determined the best-fitting global parameters of $\log(t/\text{yr}) = 9.38 \pm 0.02$ ($\sim 2.4$ Gyr), $[\text{Fe/H}] = -0.55 \pm 0.05$ dex, $A_V = 0.20 \pm 0.01$ mag, and $(m - M)_0 = 18.50 \pm 0.05$ mag. These parameters are close to those of Martocchia et al. (2018). NGC 1978 does not exhibit an extended MS turnoff region, which is a feature produced by fast stellar rotation (i.e., Li et al. 2014; Cordoni et al. 2018); the adopted rotational velocity for the best-fitting isochrone is thus zero. The uncertainty associated with each parameter is the width of the generated grid for fitting. Here the best-fitting model means it represents the optimal fitting to all four passbands.

In this work, the isochrone is only used for generating enriched stellar models. To examine the effect of chemical enrichment for different passbands, we first generate a series of synthetic spectra.

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### Table 1

| Rootname   | Camera (Aperture)         | Exposure Time | Filter    | Program ID |
|------------|---------------------------|---------------|-----------|------------|
| idxz12exq  | UVIS-CENTER/WFC3          | 1493.0 s      | F275W     | GO-15630   |
| idxz12eyq  | UVIS-CENTER/WFC3          | 1498.0 s      | F275W     |            |
| idxz12ezq  | UVIS-CENTER/WFC3          | 1500.0 s      | F275W     |            |
| idxz12f1q  | UVIS-CENTER/WFC3          | 1499.0 s      | F275W     |            |
| idxz12f2q  | UVIS-CENTER/WFC3          | 1501.0 s      | F275W     |            |
| idxz12f3q  | UVIS-CENTER/WFC3          | 1502.0 s      | F275W     |            |
| idxz13f0q  | UVIS-CENTER/WFC3          | 1493.0 s      | F275W     |            |
| idxz13f1q  | UVIS-CENTER/WFC3          | 1495.0 s      | F275W     |            |
| idxz13f2q  | UVIS-CENTER/WFC3          | 1500.0 s      | F275W     |            |
| idxz13f3q  | UVIS-CENTER/WFC3          | 1498.0 s      | F275W     |            |
| idxz13f4q  | UVIS-CENTER/WFC3          | 1492.0 s      | F275W     |            |
| idxz14j0q  | UVIS-CENTER/WFC3          | 200.0 s       | F814W     |            |
| idxz14j1q  | UVIS-CENTER/WFC3          | 349.0 s       | F814W     |            |
| idxz14j2q  | UVIS-CENTER/WFC3          | 349.0 s       | F814W     |            |
| idxz14j3q  | UVIS-CENTER/WFC3          | 200.0 s       | F814W     |            |
| idxz14j4q  | UVIS-CENTER/WFC3          | 688.0 s       | F814W     |            |
| idxz14j5q  | UVIS-CENTER/WFC3          | 348.0 s       | F814W     |            |
| idxz14j6q  | UVIS-CENTER/WFC3          | 200.0 s       | F814W     |            |
| icz611r6q  | UVIS-CENTER/WFC3          | 500.0 s       | F343N     | GO-14069   |
| icz611r7q  | UVIS-CENTER/WFC3          | 1000.0 s      | F343N     |            |
| icz611r8q  | UVIS-CENTER/WFC3          | 800.0 s       | F343N     |            |
| icz611r9q  | UVIS-CENTER/WFC3          | 425.0 s       | F343N     |            |
| icz611r0q  | UVIS-CENTER/WFC3          | 450.0 s       | F343N     |            |
| icz611r1q  | UVIS-CENTER/WFC3          | 800.0 s       | F343N     |            |
| icz611r2q  | UVIS-CENTER/WFC3          | 750.0 s       | F438W     |            |
| icz611r3q  | UVIS-CENTER/WFC3          | 650.0 s       | F438W     |            |
| icz611r4q  | UVIS-CENTER/WFC3          | 75.0 s        | F438W     |            |
| icz611r5q  | UVIS-CENTER/WFC3          | 120.0 s       | F438W     |            |
| icz611r6q  | UVIS-CENTER/WFC3          | 460.0 s       | F438W     |            |
| icz611r7q  | UVIS-CENTER/WFC3          | 420.0 s       | F438W     |            |
The radiative transfer code and line lists come from SPECTRUM.\footnote{http://www.appstate.edu/~grayro/spectrum/spectrum.html} MARCS model atmospheres and solar abundances were adopted (Gustafsson et al. 2008; Asplund et al. 2009). For stars on the best-fitting isochrone, we calculated their chemically enriched counterparts. These enriched stellar spectra have the same global parameters (log $g$, log $T_{\text{eff}}$, $X$, $Y$, $Z$) as the reference stars, but they are enriched in N and depleted in C and O, while the total abundance of CNO remains constant. For each star, their chemically enriched counterparts will exhibit different feature in the F275W, F343N, and F438W passbands (their difference in the F814W passband is very small, less than 0.001 mag), leading to measurable differences in photometry. For each star pair, we convolved both the ordinary and enriched stellar spectra with the different passbands and calculated their flux ratio. This ratio was converted into magnitude differences in different passbands. Stars with the same degree of chemical enrichment thus populate a locus with different feature in the F275W, F343N, and F438W passbands and calculated their difference in the F814W passband is very small, less than 0.001 mag, leading to measurable differences in photometry. For each star pair, we convolved both the ordinary and enriched stellar spectra with the different passbands and calculated their flux ratio. This ratio was converted into magnitude differences in different passbands. Stars with the same degree of chemical enrichment thus populate a locus with different feature in the F275W, F343N, and F438W passbands.

We calculated loci for $\Delta[N/Fe] = 0.2$, 0.4, 0.6, 0.8, and 1.0 dex, and $\Delta[O/Fe] = \Delta[C/Fe] = -0.02$, $-0.06$, $-0.13$, $-0.26$, and $-0.63$ dex. As a toy model, we assumed that both oxygen and carbon will be depleted to the same degree. These combinations are determined by the constraint of $\Delta[C+N+O]/Fe = 0$. Because MPs among RGB stars in NGC 1978 have been well studied by Martocchia et al. (2018) and Milone et al. (2020), we only calculated the MS part for each locus. In Figure 2, we present the $C_{F275W,F343N,F438W}$ versus F814W diagram of NGC 1978 (we selected F814W as the vertical axis because in this diagram the RGB and the MS are well separated), where we have also included the theoretical loci for the best-fitting isochrone and enriched stellar populations.

The model tells us that the chemically enriched stellar population would have a smaller $C_{F275W,F343N,F438W}$ index than normal stars. This can be readily expected, because an N-enriched star would have deeper NH absorption at 337 nm, leading to a lower flux in the F343N passband, thus a larger magnitude. In the meantime, the N-enriched star would be O depleted. Therefore the OH-dominated passband, F275W, would have a smaller magnitude. As a result, we obtained a smaller F275W–F343N color. In addition, the depleted C would produce shallower CH absorption at 430 nm, leading to a smaller F438W magnitude, and thus a larger F343N–F438W color. Their difference, the $C_{F275W,F343N,F438W}$ index, is thus smaller than that for its ordinary counterpart. In Figure 2 we see that the differences between different loci and the standard isochrone become more significant with increasing magnitude from F814W $\geq$ 22 mag. However, with the magnitude increase, the photometric uncertainty increases as well. To find a balance between these two effects, we finally determine an optimal magnitude range of 22.5 $>$ F814W $>$ 23.5 mag (Figure 2). This magnitude range would select the sample stars with surface temperature between 5480 K and 6370 K (K to late-G type).

In the left panel of Figure 2, we present the observed $C_{F275W,F343N,F438W}$ versus F814W diagram of NGC 1978. An asymmetry spread of $C_{F275W,F343N,F438W}$ of the MS can be seen in this diagram. This is predominantly caused by the difference of photometric uncertainties between different passbands. The “red” side (with high $C_{F275W,F343N,F438W}$) of the MS can be explained by photometric uncertainties and unresolved binaries. In the right panel of Figure 2, we present the $C_{F275W,F343N,F438W}$ versus F814W diagram of a simulated SSP sample.

We used the same method as in Li et al. (2020) to mimic a real observation. We generated a sample of ASs following the standard isochrone and N-enriched loci with a Kroupa mass function (Kroupa 2001). The total number of stars in each model population is 367,000. Unresolved binaries may play an additional role in the broadening of the MS. However, no studies have reported the MS–MS binary ratio for NGC 1978. We therefore used the same method as designed in Milone et al. (2012).
to estimate the MS–MS binary fraction. If we assume a flat mass-ratio distribution, the total GK-type MS–MS binary fraction should be 50%. However, we highlight that this must be a maximum binary fraction, as soft binaries (low-mass and low-mass-ratio binaries) would be quickly dissolved through three-body encounters in the densest region of the cluster (e.g., Geller et al. 2013). For the GK-type MS, both photometric uncertainties and unresolved binaries will lead to a broadening of the MS to the positive side of the $C_{F275W,F343N,F438W}$ index. But the photometric uncertainty is much more important than binaries. Therefore, a variation in the binary fraction from 20% to 50% would not strongly affect our results.

We generated six artificial stellar populations, including a standard SSP with $\Delta [N/Fe] = 0.0$ dex, and a series of SSPs with $\Delta [N/Fe] = 0.2, 0.4, 0.6, 0.8, \text{ and } 1.0$ dex. For each population, we divided them into 3670 sub-samples, each containing 100 stars. These sub-samples were added to the raw images and recovered using DOLPHOT2.0 following the same adoption as for the real observation. That means we have repeated these procedures 7340 times for each population ($3670 \times 2$, because we have used two observational channels). Because both the real and the synthetic population stars are measured from the same frame using the same photometric procedure, they should suffer from the same photometric effects, such as photometric uncertainty, contaminations by real objects (cosmic rays, extended sources), or bad pixels. For ASs, we reduced them following the same criteria as for the real observation. The initial spatial distribution of the ASs was uniform. Because ASs are less affected by crowding, their average photometric uncertainty is smaller than real stars. We confirmed that once we have filtered all ASs by their crowding as for the real observation, the difference between their photometric uncertainties becomes negligible. As introduced, the color variations in different baselines cannot be fully reduced from the observation due to the low signal-to-noise ratios of our sample stars, because all CNO-related molecules would be destroyed in hot stars. Therefore, the chemical variation would not affect early-type MS stars. We decided to add extra color variations ($\sim0.02–0.03$ mag) to the ASs to mimic the observed width of the MS with $F814W \lesssim 21.5$ mag.

We then constructed five synthetic MPs with different N enrichment (and C, O depletion) through mixing different SSPs. The fraction of each population stars with different chemical enrichment depends on the distribution of the chemical spread. We assumed two different chemical spread distributions: flat distribution and bimodal distribution (see the next section).

### 3.2. Statistical Analysis

We first undertake a visual inspection of the observation and the synthetic SSP and MPs. The left, middle, and right panels of Figure 3 are the $C_{F275W,F343N,F438W}$ versus $F814W$ diagrams of the observation, the synthetic SSP, and the synthetic MPs.
with 50% SG stars ($\Delta[N/Fe] = 1.0$ dex), respectively. From top to bottom are diagrams for different F814W magnitude ranges. An overall impression of Figure 3 is that the observed MS is indeed “fatter” than the synthetic SSP. In the bottom-left and middle panels we can see an excess of stars with $C_{F275W, F343N, F438W} < 1.0$ mag compare to the simulated SSP model. When considering a presence of stars with $\Delta[N/Fe] = 1.0$ dex (red dots in the bottom-right panel), the difference is released. This difference is negligible for the MS part in the range $21.0 \leq F814W \leq 21.5$ mag, which proves that we have correctly reproduced the spread where the effect of MPs is not important. For the MS part for $F814W > 21.5$ mag, the difference becomes apparent, as illustrated in the bottom panels. As one can see, the observation shows an apparent excess of stars on the blue side of the MS. This indicates a fraction of enriched population stars to reproduce the observation. The results presented in Figure 3 are in contrast to NGC 419, which exhibits a high similarity between its observed MS and the synthetic SSP (Li et al. 2020, their Figure 2).

We now discuss the effect of the measurement uncertainties, including photometric uncertainties as well as blending and PSF

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**Figure 3.** Comparisons between the $C_{F275W, F343N, F438W}$ vs. F814W diagrams of the observation (left), the synthetic single stellar population (middle) and the synthetic multiple stellar populations where 50% stars are enriched by $\Delta[N/Fe] = 1.0$ dex (right, red circles). From top to bottom are diagrams for different magnitude ranges. (SG: second generation, the chemically enriched population; FG: first generation, the pristine population.)
variations. These effects, in principle, should be reflected by ASs. In Figure 4, we present the observed $C_{F275W,F343N,F438W}$ versus $F814W$ diagram as well as two boundaries determined by tripling the measurement uncertainties and the ridge-line (top-left panel). If assuming that the measurement uncertainty is Poisson-like, only a fraction of 0.3% stars should be located outside of these two boundaries. However, in total we detected 2.0% stars that are located on the right side of the right boundary and 4.7% stars that are located on the left side of the left boundary. This is more than 20 times the expectation (2.0% + 4.7% versus 0.3%).

The excess of stars located on the right side of the boundary can be explained by unresolved binaries and field contamination residuals. Using ASs, with 50% unresolved binaries, the average fraction of stars on the right side of the boundary is 1.7% (derived from the synthetic SSP model). However, no other effect except for the measurement uncertainty and chemical enrichment could contribute stars located on the left side of the boundary. Indeed, using the synthetic SSP, we only detected 0.5% stars beyond the left boundary. The observed excess of stars on the “blue” side of the MS (blue-excess stars), therefore, has to be explained by a fraction of enriched population stars.

The first thing we explored is the degree of internal chemical spread. We generated five synthetic MPs composed of 50% pristine population stars and 50% enriched population stars with $\delta[N/Fe] = 0.2, 0.4, 0.6, 0.8, 1.0$ dex (i.e., a bimodal distribution of chemical spread). As expected, the MS becomes wider in $C_{F275W,F343N,F438W}$ with the increasing internal chemical spread. The average number fractions of blue-excess stars are 0.8%, 1.1%, 1.9%, 3.5%, and 8.2%, respectively. In Figure 4 we present one example of their $C_{F275W,F343N,F438W}$ versus $F814W$ diagrams. The average number fractions are calculated through 20 runs of AS simulations. The luminosity function (LF) of blue-excess stars is not a random distribution. Most stars have their magnitude of $F814W \sim 22.7–22.9$ mag, because in this magnitude range the photometric uncertainty is not large enough to mask the effect of chemical enrichment. We confirmed that the observed LF of these blue-excess stars is consistent with MPs with a maximum chemical spread of $\Delta[N/Fe] = 1.0$ dex (Figure 5).

We also used an alternative method to quantify the similarity between the observed and synthetic populations. We compared the distribution of $\Delta C_{F275W,F343N,F438W}$ for the observed and artificial MS stars. For both the observation and synthetic populations, $\Delta C_{F275W,F343N,F438W}$ is the deviation of the detected $C_{F275W,F343N,F438W}$ for both the real and ASs to the MS ridge-line. The MS ridge-line is determined by connecting the median $C_{F275W,F343N,F438W}$ at different $F814W$ magnitudes in steps of 0.1 mag. We then calculated the similarity between the $\Delta C_{F275W,F343N,F438W}$ distribution of the observation and synthetic populations, through a $\chi^2$ minimization method:

$$\chi^2 = \sum_{n=1}^{N} \frac{(N_i - N'_i)^2}{\sigma_i}$$

where $N$ is the number of observed stars within a given range centered at $\Delta C_{F275W,F343N,F438W}$. $N_i$ and $N'_i$ are numbers of observed/simulated stars located in the $i$th $\Delta C_{F275W,F343N,F438W}$
difference, we repeated the values as representations. To estimate the significance, we only count bins containing at least 10 stars, and all other poorly populated bins are grouped together for the calculation of \( \chi^2 \). The \( \chi^2 \) indicates the similarity between the observation and the simulated populations. In principle, the smaller the \( \chi^2 \), the higher the similarity. In Figure 6 we show that the model would be lower than the MP model. As an example, in Figure 6 we present the normalized \( \Delta C_{\text{F275W,F343N,F438W}} \) distribution of the observation (with field contamination statistically subtracted) versus that for the synthetic stellar populations with different \( \delta [\text{N/Fe}] \). To reduce the noise, we have generated 20 synthetic populations with different chemical spreads and calculated their average \( \chi^2 \) values as representations. To estimate the significance of their \( \chi^2 \) difference, we repeated the \( \chi^2 \) calculation for the SSP model 1000 times. Then we counted how many times the \( \chi^2 \) of the SSP model would be lower than the MP model. As an example, in Figure 6 we show that the \( \chi^2 \) of the MP model with \( \delta [\text{N/Fe}] = 0.8 \) dex is 61, which is smaller than in 996 of those 1000 \( \chi^2 \) values we calculated for the SSP model. We thus define its significance as 99.4%. Our result shows that \( \chi^2 \) continues to decrease for increasing \( \delta [\text{N/Fe}] \). For MPs with \( \delta [\text{N/Fe}] = 0.8 \) dex and 1.0 dex, their significances of \( \chi^2 \) are higher than 99%. We thus suggest that this result could indicate the presence of a chemical spread, with \( \delta [\text{N/Fe}] \geq 0.8 \) dex.

We then explored the number fraction of enriched population stars. This depends on the distribution of the chemical spread. The real distributions of the chemical enrichment vary from cluster to cluster. However, because of the large photometric uncertainties of the MS stars, we could not resolve the detailed distribution of their chemical enrichment distribution.

We only explored two extreme cases of chemical spread. The first model invokes a flat distribution of chemical spread. We set the pristine population as the dominant population, and all other populations with different \( \Delta [\text{N/Fe}] \) are homogeneously mixed. All synthetic MPs have an internal chemical spread of \( \delta [\text{N/Fe}] = 1.0 \) dex. For example, a MPs with 50% enriched population stars will contain 50% pristine stars, and populations with \( \Delta [\text{N/Fe}] = 0.2, 0.4, 0.6, 0.8, 1.0 \) dex occupy 10% each. We generated nine MPs with enriched population stars ranging from 10% to 90%, calculated their similarities to the observation through the \( \chi^2 \) minimization method introduced above.

In Figure 7 we present the \( \Delta C_{\text{F275W,F343N,F438W}} \) distributions. We find that the reproduction of the synthetic MPs is unsatisfactory. The optimal reproduction requires a very high fraction of enriched population stars (80%). Through visual inspection, we find that even the model with 80% enriched population stars would have a sharper \( \Delta C_{\text{F275W,F343N,F438W}} \) distribution than the observation, which may indicate that only the population with a high chemical enrichment (i.e., \( \delta [\text{N/Fe}] = 1.0 \) dex) would produce significant broadening of the MS. This forced us to find another probability of chemical spread, the bimodal distribution.

Bimodal distribution is very common for chemical spread in clusters with MPs. As an example, Niederhofer et al. (2017) find that NGC121 exhibits two distinct RGB stars which can be described by a pristine population and an enriched population with \( \Delta [\text{N/Fe}] = 1.1 \) dex. We employ a bimodal distribution which only contains a pristine population and an enriched population with \( \Delta [\text{N/Fe}] = 1.0 \) dex. We vary the fraction of enriched population stars from 10% to 90% and calculate the
same $\chi^2$ to quantify their similarities to the observation. This result is presented in Figure 8.

In Figure 8 we find that, with a bimodal chemical distribution, 40% of enriched stars can make the optimal reproduction. Compared with the optimal reproduction in Figure 7, the $\Delta C_{F275W,F343N,F438W}$ distributions in Figure 8 also exhibit a better fit to the observation, with a lower $\chi^2$ (40). The flat and bimodal distributions represent two extreme cases of chemical spread; the real distribution of chemical spread should be some shape between these two cases. In this work, we therefore conclude that the distribution of chemical spread for the observation is more likely a bimodal rather than a flat distribution. The fraction of enriched population stars among the GK-type MS of NGC 1978 would range from 40% (bimodal) to 80% (flat).

Finally, in Figure 9, we present the observed $C_{F275W,F343N,F438W}$ versus $F814W$ diagrams as well as the “best-fitting” synthetic MPs for two different chemical distributions: a flat distribution with 80% enriched stars and a bimodal distribution with 40% enriched population stars. For the observed $C_{F275W,F343N,F438W}$ versus
F814W diagrams, the field contamination has been statistically subtracted based on the selected “reference field” (with completeness and area difference corrected). We find that a bimodal distribution with 40% enriched stars exhibits a higher similarity to the observation than the flat distribution model (70% enriched stars).

4. Discussion and Conclusion

The very large photometric uncertainties prevent us from resolving the stellar populations in detail. As shown in Figure 6, an internal chemical spread of $\delta[\text{N}/\text{Fe}] \lesssim 0.6$ dex would not be very different from the SSP model. As a result, even if these dwarfs are MPs with some modest chemical spread, our analysis could not uncover this signature. In this work, to minimize the effect of large photometric uncertainties, we have considered many physical and artificial effects, including differential reddening, PSF-fitting variations, and color variations. Some of these effects can be partially corrected in our AS sample, and some have to be considered as additional noise that we cannot reduce. Given that we have considered all (major) uncertainties and contaminations, the presence of MPs is the most reasonable explanation for the observed color spread of the MS.

Figure 8. As Figure 7, but the chemical spread follows a bimodal distribution ($\Delta[\text{N}/\text{Fe}] = 0.0$ and 1.0 dex).
4.1. Radial Distribution of Multiple Populations

A recent study has revealed a clear evolution of the spatial mixing between pristine and enriched stars as a function of dynamical stage among different GCs (Dalessandro et al. 2019). The dynamical evolution of clusters can readily explain this result with an initially more concentrated enriched population. If different population stars indeed cause the broadening of the MS of NGC 1978, we may see the difference in their central concentration. We employed a poor man’s method by dividing the GK-type stars into two subgroups with $\Delta C_{F275W,F343N,F438W} > 0$ and $\Delta C_{F275W,F343N,F438W} < 0$. Based on our model, the sample with negative $\Delta C_{F275W,F343N,F438W}$ would contain more enriched stars than the sample with positive $\Delta C_{F275W,F343N,F438W}$. We thus define the sample with $\Delta C_{F275W,F343N,F438W} > 0$ as the “first generation” (FG), and its counterpart as the SG. Based on Dalessandro et al. (2019), we should see that the SG is more centrally concentrated than the FG because NGC 1978 is much younger than most GCs.

In the top panel of Figure 10, we show the cumulative curves of FG and SG as functions from the cluster center to $R_{hl}$. We find a very significant difference between the FG and SG, where the SG is indeed more centrally concentrated than the FG. We then explore if this concentration difference is simply caused by observational artifacts such as blending or different sky levels for stars with different $\Delta C_{F275W,F343N,F438W}$. This is examined through AS tests. In the bottom panel of Figure 9, we did not find any significant difference in central concentration of ASs with positive/negative $\Delta C_{F275W,F343N,F438W}$. Actually, contrary to the observation, we find that ASs with positive $\Delta C_{F275W,F343N,F438W}$ are slightly more centrally concentrated than ASs with negative $\Delta C_{F275W,F343N,F438W}$. This is caused by the presence of unresolved binaries. Therefore the fact that the SG would have a higher central concentration than the FG cannot be explained by observational artifacts. The observed different concentrations between the FG and SG are a physical reality.

4.2. The Fraction of Enriched Population Stars

Accurate determinations of the fraction of N-rich stars is challenged by photometric uncertainties and residual differential reddening. The amount of differential reddening associated to each star corresponds to the median reddening of a sample of 30 neighbors (see Milone et al. 2012). Hence, our differential-reddening correction does not account for very small-scale reddening variations, because the internal spreads of differential reddening and color variations for these nearest stars cannot be corrected, and they will contribute to additional broadening of the MS as well. That means we may have overestimated the fraction of enriched stars. But this overestimation should be minor, as the typical residuals of the differential reddening and color variations could be only roughly their internal spread (after correction) divided by the number of nearest stars we used. In summary, if we assume a bimodal distribution in chemical spread, the minimum fraction of enriched population stars is $\sim 40\%$, which is more than twice that found by Milone et al. (2020) (15%).

We estimate the initial mass of NGC 1978. If we assume that the initial stellar mass function (IMF) of NGC 1978 is Kroupa-like, depending on polluters, the mass fractions of different polluters varies from 7% (massive binaries; de Mink et al. 2009)
to 15% (intermediate-mass AGB stars; Bekki 2017). If assuming a realistic maximum star formation efficiency of 30% (Lada & Lada 2003), the initial mass of NGC 1978 should be at least nine times its current mass.

We then evaluate the dynamical age of NGC 1978. We calculated the brightness profiles of NGC 1978 in F275W and F814W passbands. We then fitted these brightness profiles using the Elson–Fall–Freeman (EFF) function (Elson et al. 1989). The brightness profiles in F275W and F814W are mutually consistent with each other. We determined an average half-light radius of $r_h = 12.0 \pm 1.7$ pc based on their best-fitting EFF functions. Next, we counted the number of stars within the range below 1–2 mag of the turnoff point in the F814W passband. We assumed that these stars belong to a Kroupa-like mass function (Kroupa 2001). By extrapolating the whole population down to the minimum stellar mass of 0.08 $M_\odot$, we estimated the total mass of NGC 1978 (assuming that its half-light radius is roughly the same as the mass-radius half). Our result yields $\log M/M_\odot = 5.28^{+0.04}_{-0.06}$ for NGC 1978, which is close to Baumgardt et al. (2013). Finally, the half-mass relaxation time is calculated as (Spitzer 1969),

$$t_{th} = \frac{0.78 \text{ Gyr}}{\ln \lambda \frac{\ln N}{m}} \left(\frac{M}{10^7 M_\odot}\right)^{1/2} \left(\frac{r_h}{1 \text{ pc}}\right)^{3/2}$$

with $\lambda = 0.1$ (Giersz & Heggie 1994). Our result yields $t_{th} = 4.62^{+0.46}_{-0.43}$ Gyr, which is more than twice the age of NGC 1978. Therefore NGC 1978 must be a dynamically young stellar system.

However, our result is in contradiction with numerical simulations, which show that FG and SG stars will be fully mixed when a cluster has lost 60%–80% of its initial mass (Vesperini et al. 2013; Miholics et al. 2015). If the numerical simulations are correct, it may indicate that the initial mass of NGC 1978 is not so high. For example, its IMF may be top-heavy rather than Kroupa-like. In any case, so far no embedded cluster is known to have such a high initial mass in the Magellanic Clouds. As suggested by Li et al. (2019), searching for young clusters with initial masses higher than this mass threshold would allow us to disentangle the various scenarios for the formation of MPs.

4.3. Summary

Our results indicate that MPs are present among the GK-type MS stars of NGC 1978. This is expected since NGC 1978 is already confirmed to harbor MPs among its RGB stars (Milone et al. 2020). In our Figure 1, we also see a clear $C_{\text{F275W,F343N,F438W}}$ broadening of its RGB. This result confirms that the MPs in NGC 1978, like most GGCs, are a global feature for stars at different stellar evolutionary stages. Since the unevolved GK-type dwarfs are not hot enough to trigger the CNO-chain, their chemical anomaly must be produced through other polluters, i.e., massive stars.

In summary, after our study of NGC 419, this work is the second attempt at searching for MPs among GK-type dwarfs in clusters with ages around $\sim 2$ Gyr. We summarize our results as follows.

1. The GK-type MS dwarfs in NGC 1978 exhibit a large $C_{\text{F275W,F343N,F438W}}$ spread, which cannot be entirely reproduced by observational uncertainties. This fact demonstrates that NGC 1978 hosts MPs among its MS stars.
2. To reproduce the observed $\Delta C_{\text{F275W,F343N,F438W}}$ distribution, we require an internal chemical spread of $\delta [\text{N}/\text{Fe}] = 1.0$ dex.
3. By assuming a flat distribution of the C, N, O stellar content, we find that a fraction of 60%–80% SG stars is required to properly reproduce the observations. A bimodal distribution of light elements composed of 40% of 2G stars, would provide a better match with the observations than that provided by flat elemental spread.
4. Stars with negative $\Delta C_{\text{F275W,F343N,F438W}}$ are more centrally concentrated than stars with positive $\Delta C_{\text{F275W,F343N,F438W}}$.

We conclude that NGC 1978 harbors a chemical spread of up to $\delta [\text{N}/\text{Fe}] = 1.0$ dex (with $\delta [\text{C}/\text{Fe}] = \delta [\text{O}/\text{Fe}] = -0.63$ dex) among its GK-type MS stars. The fraction of enriched stars is at least 40%. The pristine and enriched stars are different in spatial distribution, with the enriched stars more centrally concentrated than the pristine population stars, similar to what is seen in most GCs. We suggest that, for most GGCs, MPs are a global feature for stars at different evolutionary stages in extragalactic star clusters.

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