A Multiwavelength Study of the Segue 3 Cluster

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Abstract

We present new SDSS and Washington photometry of the young outer-halo stellar system Segue 3. Combined with archival VI-observations, our most consistent results yield $Z = 0.006 \pm 0.001$, $\log(Age) = 9.42 \pm 0.08$, $(m - M)_0 = 17.35 \pm 0.08$, and $E(B - V) = 0.09 \pm 0.01$, with a high binary fraction of $0.39 \pm 0.05$ derived using the Padova models. We confirm that mass-segregation has occurred, supporting the hypothesis that this cluster is being tidally disrupted. A three-parameter King model yields a cluster radius of $r_c = 0.017 \pm 0.007$, a core radius of $r_c = 0.003 \pm 0.001$, and a tidal radius of $r_t = 0.04 \pm 0.02$. A comparison of Padova and Dartmouth model-grids indicates that the cluster is not significantly $\alpha$-enhanced, with a mean [Fe/H] = $-0.55^{+0.15}_{-0.12}$ dex, and a population age of only $2.6 \pm 0.4$ Gyr. We rule out a statistically significant age spread at the main-sequence turnoff because of a narrow subgiant branch, and discuss the role of the stellar rotation and cluster age, using Dartmouth and Geneva models: approximately 70% of the Seg 3 stars at or below the main-sequence turnoff have enhanced rotation. Our results for Seg 3 indicate that it is younger and more metal-rich than all previous studies have reported to date. From colors involving Washington C and SDSS-u filters, we identify several giants and a possible blue straggler for future follow-up spectroscopic studies, and we produce spectral energy distributions of previously known members and potential Seg 3 sources with Washington (CT1), Sloan (ugri), and VI-filters. Segue 3 shares the characteristics of unusual stellar systems that have likely been stripped from external dwarf galaxies as they are being accreted by the Milky Way, or that have been formed during such an event. Its youth, metallicity, and location are all inconsistent with Segue 3 being a cluster native to the Milky Way.

Key words: globular clusters: individual (Segue 3)

Supporting material: machine-readable tables

1. Introduction

A form of so-called stellar archaeology traces the formation of the Milky Way (MW) using the dense globular clusters (GCs) as test particles. However, it has become obvious that GC populations are far more chemically diverse than we assumed a few decades ago, and are not simple single-generation star populations (Gratton et al. 2012, and references therein). The MW contains at least 150 GCs, and there appears to be a difference between the inner- and outer-halo populations (VandenBerg et al. 2013).

Segue 3 was first discovered by Belokurov et al. (2010) in the Sloan Digital Sky Survey (SDSS) $(\alpha = 2^h 2^m 3^s 1^f, \delta = +19^\circ 07^\prime 02^\prime\prime J2000, l = 69.4, b = -21.27^\circ)$, and was identified as an ultra-faint star cluster with a half-light radius $r_h = 0.065 \pm 0.1$. The discovery paper detailed KPNO 4 m g and r photometry used to derive the structure of Segue 3, employing an M92-like template isochrone. Belokurov et al. (2010, hereafter B10) found $(m - M)_0 = 16.3$ and $[Fe/H] = -2.3$, which indicated that Seg 3 is a cluster similar to Koposov 1 and 2 (Koposov et al. 2007). The authors tentatively linked Segue 3 with the structure of the Hercules-Aquila Cloud.

Fadeley et al. (2011, hereafter, F11) used Keck/DEIMOS spectroscopy and Magellan/IMACS g- and r-band imaging of Seg 3, coupled with maximum likelihood methods, to analyze the structure of the star cluster. F11 found a smaller $r_h$ of 26 arcsec, with an age of 12$^{+1.5}_{-0.4}$ Gyr and $[Fe/H] = -1.7^{+0.07}_{-0.27}$. F11 identified 32 member-stars from spectroscopy and photometry, and placed 11 of the stars outside three of their half-light radii, finding no evidence of dark matter. F11 support B10’s conclusion that Seg 3 is an old, faint, and sparse star cluster. B10 note that the evolution of a system like Seg 3 proceeds, with more massive objects collecting at the core of the cluster and less massive objects forming a halo, as the cluster disrupts. Kim & Jerjen (2015) discuss the cluster Kim 1, mentioning Seg 3; they concluded that since F11 found a radial-velocity offset between Seg 3 and the Hec-Aql Cloud, they were not likely to be connected.

In contrast, Ortolani et al. (2013, hereafter, O13) used deep Galileo (Telescopio Nazionale Galileo) B, V, and I images of Segue 3 ($V \leq 25$) to determine an age of $3.2 \pm 0.8$. The O13 result characterized Segue 3 as the youngest GC in our Galaxy. Its likely youth may imply that Seg 3 is a captured object or a system formed during a capture of a gas-rich dwarf (O13; F11). Such gas-rich dwarf galaxies (e.g., WLM, SMC, LMC) may have donated clusters with properties similar to those of Palomar 1 (Sarajedini et al. 2007; Sakari et al. 2011) and Segue 3 to the MW. With a well-defined MSTO in their $V$ versus $(V - I)$ color-magnitude diagram (CMD), O13 found $(m - M)_0 = 17.32$, $d_c = 29.1$ kpc, with Galactic coordinates of $X = -13.0$, $Y = -6.1$, and $Z = -19.2$, making its Galactocentric distance $R_{GC} = 24.0$ kpc; this places it among the unusual outer-halo faint clusters.

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A study by Paust et al. (2014) identified Ko 1 and 2 as open clusters (OCs) of ages 5–7 Gyr, with [Fe/H] = −0.60 and [α/Fe] = +0.2, that could have been lost by the Sagittarius dwarf galaxy, and are part of the Sagittarius Stream. The conclusion of these authors was based on evidence that the luminosity functions (LFs) of these clusters did not show significant mass loss. O13's V-band LF shows that the main sequence of Segue 3 is depleted above their completeness limit, indicating that it has undergone significant tidal stripping, and probably was a more massive system in the past.

O13 argued that the main difference in their results and those of F11 was caused by an offset (of unknown origin) in the latter's photometry, and the inclusion or exclusion of a few subgiant branch (SGB) stars. No red giant branch (RGB) objects have been conclusively identified as members of Segue 3 from past studies (B10, F11, O13), and no spectroscopic metallicities have been reported. As the "youngest GC" (O13) in the MW, this is an important system, which merits further study. We attempt to reproduce the previous results in Section 2.1, using the archival O13 data. In this paper, we study Segue 3 with Washington (Section 2.2) and SDSS (Section 2.3) filters, both to provide more wavelength coverage and to reduce the observational uncertainties in the age and metallicity. The (C − T I) and (μ − g) colors are around two to three times more sensitive than (V − J) and (g − r) (Geisler & Sarajedini 1999; Li & Han 2008; Hughes et al. 2014, depending on metallicity and age). A discussion in Hughes et al. (2014, and references therein) compared previous papers that tested the most effective color pairs in use for age and metallicity studies (Li & Han 2008; Holtzman et al. 2011, etc.), noting that the theoretical colors were tested on relatively close and dense GCs.

To avoid user bias as much as possible, we compared the results of fits to the Dartmouth models (Dotter et al. 2008; Dotter 2016) made with simple χ²-fitting routines for multiple colors, with more complex open-source codes that claim to simultaneously fit 7–9 parameters that are degenerate in CMDs or color-color plots. We also chose two different codes, one that has been tested on OCs, and one designed for GCs. To compare directly with O13, who used the Bressan et al. (2012) models, we employed the PARSEC (Bressan et al. 2012), stellar tracks and isochrones with the PAdova and TRieste Stellar Evolution Code) and the (open-source) Automated Stellar Cluster Analysis (ASteCA) suite of modeling tools (Perren et al. 2015, Section 2.1).

To better estimate the observational uncertainties, compared to the standard age-metallicity scale (VandenBerg et al. 2013) for GCs, we used BASE-9 (von Hippel et al. 2014; Stenning et al. 2016; Wagner-Kaiser et al. 2016a). This is another Bayesian modeling code that fits star cluster basic parameters, but it requires that cluster membership is assigned to stars in the region, and Segue 3 is a sparse stellar cluster in a crowded field. An advantage of the ASteCA suite of tools is that it contains a "Bayesian field star decontamination algorithm capable of assigning membership probabilities using photometric data alone" (Perren et al. 2015). BASE-9 can be used for single-age and single-metallicity clusters (Wagner-Kaiser et al. 2017), but can also be set to model clusters that differ internally in helium abundance (Stenning et al. 2016; Wagner-Kaiser et al. 2016b), using the Y-enhanced Dartmouth isochrones (DO8). For completeness in considering stellar rotation as a free parameter, we also compared our data with the Geneva model database (Georgy et al. 2013), which allows for a wider range of stellar rotation rates than the Dartmouth models.

Without medium- to high-resolution spectroscopy, we cannot confirm that Segue 3 is (or was, before it was so severely stripped: O13, F11, B10) a standard GC, with the Na–O anticorrelation, denoting multiple populations (Gratton et al. 2012). Helium enhancement can affect colors and might be a valid discriminator between OCs and GCs. We also searched for similarities between Segue 3 and the LMC and SMC young massive clusters (Bastian 2016, YMC, and references therein).

We detail our observations in Section 3. In Section 4 we discuss the spectral energy distributions (SEDs) and ensure all the photometry (UV–IR) can be calibrated to a uniform metallicity scale for cluster members and possible RGB stars, and one likely blue straggler (BS). In Section 5 we discuss the possibility that we are observing a spread in rotation rates instead of a large age-uncertainty at the turnoff. We address the age-metallicity relationship for galactic GCs in Section 6, and we place Segue 3 in a group of unusual outer-halo systems that might be extragalactic in origin.

2. Method

2.1. Comparison of VI-data with the Padova Models

We obtained the archival O13 data (noting that uncertainties are not available) and display the ASteCA fits in Figures 1 and 2. Figure 1 shows the source density map, the three-parameter (3P) King model fit, and the finding chart for objects scaled by V mag. Figure 2 shows the V, V−I ASteCA cleaning process, where 10 field regions were defined around the cluster. For the O13 field of view (FOV), relaxing or tightening the cluster-membership criteria in the code (Perren et al. 2015) selected >50 members in those filters. We show one run for the data, setting the visual
extinction range from 0.05 < E(B−V) < 0.20 mag, as we found that ASteCA can only reproduce the O13 results exactly by limiting the input interstellar extinction and by forcing Z < 0.005. The lack of a well-defined RGB requires us to limit the extinction range; our tests added artificial stars to an assumed RGB to confirm this. We limited the distance modulus to 15–20 mag and let all other parameters range over the usual Padova/PARSEC12 model grid (Bressan et al. 2012): we searched a log(Age) range from 6.0 to 10.13 and a metallicity range from Z = 0.0001 to 0.015. We ran the code in manual and automatic mode to test the stability of the fit to a cluster with known members (F11 and O13) outside the apparent cluster radius.

We took the extinction values from the Schlegel et al. (1998, hereafter: SFD) IRAS maps, noting that the MSTO magnitude/color is very sensitive to the assumed extinction, and can change the age and metallicity considerably in fitting isochrones. For the extinction corrections we assume the relationships given in Equations (1)–(8). In the Washington filters, we use standard relationships from Geisler et al. (1991) and Geisler & Sarajedini (1999, hereafter: GS99) for Washington filters and those listed by (Yuan et al. 2013, and SFD). GS99 use Ap = 3.2E(B−V); not setting RV = 3.1 does not transform into an appreciable difference with low E(B−V), but R values might vary in different galaxy environments. Previous studies found that these relationships would return photometric metallicities that compared well to spectroscopic measurements (Hughes et al. 2008, 2014). Both O13 and F11 results agree with the SFD/IRAS maps: E(B−V) ≈ 0.1, and extinction does not appear variable.

\[
E(V - I) = 1.24E(B - V); \quad (1)
\]
\[
E(C - T_i) = 1.97E(B - V); \quad (2)
\]
\[
E(T_i - T_2) = 0.69E(B - V); \quad (3)
\]
\[
M_{T_i} = T_i + 0.58E(B - V) - (m - M)_V; \quad (4)
\]
\[
u_0 = u - 5.14E(B - V); \quad (5)
\]
\[
g_0 = g - 3.79E(B - V); \quad (6)
\]
\[
r_0 = r - 2.75E(B - V); \quad (7)
\]
the number of likely cluster members. For this example, the O13 FOV has a value of CI = 0.34; where a value >0.5 would indicate an equal number of field and cluster stars. Perren et al. (2015) discuss the limitations of this code when dealing with a heavily contaminated region. The photometry is listed in O13 to \( V \approx 25 \) (no uncertainties), although the ASteCA routines calculate \( V \approx 23.6 \) as the completeness limit. The ASteCA analysis was tested on 400 MASSCLEAN-generated clusters (Popescu & Hanson 2009) by Perren et al. (2015), who also modeled 20 MW OCs, where Segue 3 is at the lower-mass end of the OC sample they used.

2.2. Washington Filters

In addition to studying the ASteCA error analysis from Perren et al. (2015), we tested the code ourselves on Washington photometry of several GCs, most notably NGC 6397 and 47 Tuc, which were used as cluster standards in Hughes et al. (2007) for comparison with the massive unusual GC, NGC 6388. We chose these two clusters since they are close to the values of [Fe/H] reported by F11 and O13 for Segue 3. NGC 6397 was modeled as \( Z = 0.0005 \pm 0.0001 \), which becomes [Fe/H] = −1.92 ± 0.11 translated into the \( \alpha \)-enhanced scale from [Fe/H] = −1.6 (solar-scaled). Vandenberg et al. (2013) reports [Fe/H] = −1.99. Also, log(Age) = 10.1 ± 0.05, \( E(B-V) = 0.14 \pm 0.02 \), \( (m-M)_0 = 12.19 \pm 0.04 \), and the binary fraction is found to be 0.30 ± 0.09. For 47 Tuc, the results were \( Z = 0.0027 \pm 0.0002 \), which is [Fe/H] = −0.82 ± 0.06 (solar-scaled), log(Age) = 10.1 ± 0.05, \( E(B-V) = 0.04 \pm 0.02 \), and \( (m-M)_0 = 13.33 \pm 0.07 \). However, the binary fraction returned by the code was too high at 0.50 ± 0.06; this GC has a broader MSTO, and it is a very crowded field for ground-based telescopes, producing more blended stellar images than a sparse cluster. The ASteCA code was able to fit isochrones with a reasonable match to accepted literature-values for these GCs, which should bound the range in metallicities expected, and the OC data showed that the ages were acceptable for much younger systems.

The Washington filters (Canterna 1976) \( C \) and \( T_1 \) have advantages over other photometric systems because of the short integration times of the broadband filters, the metallicity sensitivity, and the wealth of previous studies of galactic and extragalactic GCs (Geisler et al. 1991, GS99). A recent paper (Cummings et al. 2017) discussed the importance of the \( C \)-filter over the narrower SDSS-\( u \), also examining F336W, for the study of multiple populations in GCs. Specifically, the paper concentrates on NGC 1851, on the RGB and SGB, and notes that the \( C \)-filter could be more effective at detecting multiple MSs. Cummings et al. (2017) also note that \( C \) and F336W can be affected by CN/CH variations. The original metallicity indicators were \((M - T_1)\) and \((C - M)\), with the latter color used most for metal-poor stars (Geisler 1986; Geisler et al. 1991). Most previous extragalactic studies used the \((C - T_1)\)-color (Geisler & Forte 1990): it is very sensitive to age and metallicity on the RGB (GS99). For [Fe/H] < −2.5, only the Washington \( C \)-filter was found to be very sensitive to \( \alpha \)-enrichment (Hughes et al. 2014), with its center at 3900 Å and a FWHM of 1100 Å (Canterna 1976). The \((C - T_1)\) or \((C-Kron-Cousins)\) R, which is more commonly used (GS99), does lose some metallicity resolution around [Fe/H] < −2. However, testing of artificial stars with metallicities ranging

### Table 1

| UT      | Imager  | Filter | t (s) | Airmass | FWHM (") |
|---------|---------|--------|-------|---------|-----------|
| 2013 Aug 17 | SPIcam | g      | 300.0 | 1.03    | 0.9       |
| 2013 Aug 17 | SPIcam | g      | 300.0 | 1.03    | 0.8       |
| 2013 Aug 17 | SPIcam | g      | 300.0 | 1.06    | 0.6       |

Notes.

- a Year-month-day.
- b \( R \) is converted into Washington \( T_1 \).
- c Effective airmass.

(This table is available in its entirety in machine-readable form.)
from $-2.5 < [\text{Fe/H}] < -0.5$ (generated from the Dartmouth models in Hughes et al. 2014) showed that $(C - T_i)$ should have twice the sensitivity of $(V - I)$ in finding the metallicity of a star cluster with $[\text{Fe/H}] \approx -1.8$, and improves for higher-metallicity systems.

### 2.3. SDSS Filters

Along with Washington $(C - T_i)$, the SDSS-color, $(u - g)$, is the most sensitive to age and metallicity for RGB stars, but it is much more sensitive at low $(\text{Fe/H} < -2)$ metallicities (Hughes et al. 2014). The advantage of using SDSS filters over the Washington colors is having the standards in the field for relative photometry. However, the $u$-band is centered at 355 nm with a width of only 57 nm, compared with a center of 398 nm and a width of 110 nm for $C$, making the former require much more observing time. For catalog data from SDSS DR13, the Seg 3 region is complete for $g \approx 23.0$ mag, for the $(g - r)$ CMD, but only $g \approx 18.9$ mag, for the $(u - g)$ color when using sources with uncertainties smaller than 0.25 in the CMD.

### 3. Apache Point Observatory (APO) Observations

We used the Apache Point Observatory (APO) new ARCTIC Imager and the camera it replaced, SPIcam for our observations with the 3.5 m telescope. The ARCTIC camera has a 4096 × 4096 STA chip giving $7.5 \times 7.5$ as the FOV when the new 5-inch diameter circular filters are used. The older Washington filters are $3'' \times 3''$ and vignette the FOV. SPIcam had a FOV of $4.8 \times 4.8$. We have several filter wheels that can handle up to ten $3 \times 3$ inch square filters (fewer in full-field mode), where binning 1 × 1 yields 0.11 arcseconds/pixel. The fastest readout time in 2 × 2 binned mode is about 5 s. The blue-UV sensitivity of ARCTIC is greater than that of SPIcam, which was a backside-illuminated SiTe TK2048E 2048 × 2048 pixel CCD with 24 micron pixels, which we also binned $(2 \times 2)$, giving a plate scale of 0.28 arcsec per pixel. Where we combined the data sets, we binned ARCTIC $2 \times 2$ and slightly degraded its resolution. We found no irreducible color terms between frames taken with both imagers, internally. From 2013 to 2015, we had 11 half-nights total, and 102 frames had seeing better than $2''$, many of which were under photometric conditions, and several nights had subarcsecond seeing. Some of the observations were repeated between SPIcam and ARCTIC, which served to test the new imager.

We observed Seg 3 in $CT_1$ and $ugri$ filters with both SPIcam and ARCTIC. The frames used are listed in Table 1, the overlap between this paper and the $V$-data from F11 (not the $g$ and $r$ mag values) and O13 is detailed in Table 2. Our photometry is presented in Table 3 for all 218 objects detected in our FOV in $CT_{ugri}$-filters, where we required detections in all filters in order to produce SEDs. We include the $z$-filter from SDSS DR13 and any 2MASS objects detected, for completeness. We compare the FOV of O13 and the multiband data we collected in Figure 3(a) and the source density for our sample in Figure 3(b), showing the asymmetry of Segue 3.

We both reduced and analyzed the data taken each night, separately, and then median-filtered the images, weighted according to the FWHM of each image, scaled appropriately, to obtain the best source-list for the FOV. The Washington photometry was calibrated to the standard system using the Washington standard fields (Geisler 1996) and absolute photometry. For the SDSS filters, we performed relative photometry with the SDSS catalog objects in the FOV. Within IRAF we used zerocombine with ccdproc to correct the flats and object frames, then flatcombine and ccdproc to flatfield the object frames. We then rotated, aligned, and matched the ARCTIC and SPIcam images (making the former fit the latter’s

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**Table 2**

Cross-identification of Objects in the Segue 3 Field

| ID#    | SDSS     | Flag | R.A. (deg.) | Decl. (deg.) | $X_C^{\circ}$ | $Y_C$ | $V_c$ (km s$^{-1}$) | $k_{O13}$ | $V_{O13}$ |
|-------|----------|------|-------------|--------------|---------------|-------|-------------------|----------|----------|
| 2     | J212132.25+190527.5 | D    | 320.384375  | 19.090972    | 389.819       | 14.178| ...               | 20.167   | 21.05    |
| 3     | J212136.46+190539.3 | G    | 320.401958  | 19.09425     | 176.979       | 55.689| ...               | 20.394   | 21.852   |
| 5     | J212131.36+190548.8 | C    | 320.380667  | 19.096889    | 434.675       | 89.991| ...               | 19.756   | 21.372   |
| 6     | J212132.28+190552.0 | C    | 320.3845    | 19.097806    | 388.314       | 101.658| −163.3            | 18.806   | 19.695   |

**Notes.**

a SDSS DR13 photometric quality grade A–C indicates few warning flags, D–F is untrustworthy, G is a galaxy.

b From Figures 3(b) and 9.

(This table is available in its entirety in machine-readable form.)

**Table 3**

Segue 3: Sources with Detections in All Filters

| ID#    | $T_1$     | $\sigma_1$ | $C$  | $\sigma_C$ | $u$  | $\sigma_u$ | $g$  | $\sigma_g$ | $r$  | $\sigma_r$ | $i$  | $\sigma_i$ | $z^{\alpha}$ | $\sigma_z$ |
|-------|-----------|------------|------|------------|------|------------|------|------------|------|------------|------|------------|--------------|------------|
| 2     | 20.640    | 0.010      | 21.972| 0.022      | 22.683| 0.033      | 21.396| 0.015      | 20.903| 0.025      | 20.668| 0.037      | 20.42         | 0.14       |
| 3     | 21.117    | 0.031      | 23.278| 0.055      | 23.666| 0.088      | 22.414| 0.046      | 21.359| 0.050      | 21.290| 0.074      | 20.34         | 0.16       |
| 5     | 20.519    | 0.009      | 23.258| 0.041      | 24.377| 0.124      | 22.026| 0.017      | 20.789| 0.018      | 20.685| 0.028      | 20.25         | 0.12       |
| 6     | 19.259    | 0.007      | 20.739| 0.011      | 21.588| 0.016      | 20.099| 0.006      | 19.467| 0.014      | 19.229| 0.022      | 19.05         | 0.05       |
| 7     | 19.122    | 0.011      | 20.886| 0.017      | 21.859| 0.019      | 20.121| 0.008      | 19.471| 0.029      | 19.225| 0.042      | 18.92         | 0.04       |

**Note.**

a Taken from SDSS DR13.

(This table is available in its entirety in machine-readable form.)
coordinate system) for each filter. We used the DAOPHOT program suite within IRAF, using ∼30 stars to create a point-spread function for each image, and employed two runs of allstar to find all sources. We found that this field is not as crowded as a normal GC when artificial star tests were performed, and that the ASteCA completeness limits are consistent with the manual experiments. For the Washington filters, we took the photometry measurements of three different nights for each star and averaged them (weighted by errors) to use in transforming magnitudes from the coadded images to the standard system. We constructed a plate solution to match with SDSS catalog objects, and also compared these with the $O13$ measurements. All the results are summarized in Tables 2 and 3. Comparing our data with those in the literature, there are 38 stars in both our observations and $F11$, 176 stars in both our observations and $O13$, and 38 stars are covered by all three studies. In Table 2, 27 stars have $V_r$ that indicates they are Seg 3 members, as reported by $F11$, with $V_r = 167 \pm 30 \text{ km s}^{-1}$. In the SDSS DR13, 176 objects are cataloged, of which 35 are also in the 2MASS survey.

As discussed earlier, $O13$ compared their data to $F11$’s photometry, where the published data was dereddened by $E(B - V) = 0.1$ mag, and found that $F11$ magnitudes appear to have a zero-point offset (of ∼0.09 mag.). We concur with $O13$’s assessment, $F11$’s data are also offset from our $g$ and $r$-magnitudes by ∼0.1 mag, where our data were originally calibrated to SDSS Data Release 12, (DR12) but have been updated to DR13. (SDSS Collaboration et al. 2016).

Figure 4 is a final sanity check on the photometric calibrations between our SPIcam, ARCTIC, SDSS DR13, and 2MASS. We show SEDs of the 25 brightest stars in our FOV in Figure 3 that were not saturated in SDSS DR13. The $CT_{1/8\sigma}$-filters (red filled triangles) are displayed, where the error bars are smaller than the points. The SDSS-$z$ and 2MASS $JHK$-magnitudes are shown as filled circles. All the plots shown are on the same logarithmic scale, apparent flux density versus wavelength in microns.

Since the FOV contains a sparse cluster and (we expect) numerous binaries ($O13$), we ensured that the stars did not have...
SDSS-flags from SDSS DR13 warn that the photometric quality was compromised in any manner, and no greater than 1% uncertainties. The object number corresponds to Tables 2 and 3. Our photometry, scaled to that of SDSS DR13, is shown for the $CT_1$-filters (red filled triangles), where the error bars are smaller than the points. The SDSS-$z$ and 2MASS $JHK$-magnitudes are shown as filled circles. All the plots shown are on the same logarithmic scale, apparent flux density against wavelength in microns.

$$u_{\text{DR13}} = u_{\text{DR12}} - 0.004, \quad \sigma_u = 0.010.$$  \hspace{1cm} (13)

These uncertainties were added in quadrature with each object’s photometric uncertainties from DAOPHOT; the final uncertainties are listed in Table 3. The i-band magnitudes are only used in the SEDs and not for any model fitting, as $(r - i)$ is a temperature-sensitive color. The range of the $(u - g)$, $(g - r)$, and $(r - i)$ colors for the 25 stars was $+1.05$ to $+2.11$, $-0.12$ to $+0.82$, and $0.00$ to $+0.29$ mag, respectively. We included star 26 in our calibration since it is the only A-type star in the sample, noting that it is in the cluster center and the crowded field might affect the photometry in the SDSS catalog (we gave it a C grade, see Table 2).

The uncertainties versus magnitudes for sources inside (red circles) and outside (blue circles) the cluster radius (from the AStECA fit for O13) are shown in Figure 5, with objects too faint to be used in any fit shown as cyan crosses. We required that the objects used be detected in all the $CT_1$-filters to allow for SED checks, but we rejected any object with large

\[ i_{\text{DR13}} = i_{\text{DR12}} - 0.4194 \times (r - i)_{\text{DR12}} + 0.1221, \quad \sigma_i = 0.010; \]  \hspace{1cm} (10)

\[ r_{\text{DR13}} = r_{\text{DR12}} + 0.0151, \quad \sigma_r = 0.003; \]  \hspace{1cm} (11)

\[ g_{\text{DR13}} = g_{\text{DR12}} + 0.0144, \quad \sigma_g = 0.003; \]  \hspace{1cm} (12)
photometric uncertainties ($\sigma > 0.25$) in any color in the following analyses.

### 3.1. Padova Fits for Washington and SDSS Colors

In Figure 6 we show three of the runs for the combined data set, showing the extremes of the fit to the Padova model grid—the $(u - g)$ results indicate higher metallicities, which may mean that this color is more sensitive to $\alpha$-abundances in general, but the CMD below the MSTO is also almost vertical and hides the binary sequence, which is much clearer in $(V - I)$ and $(C - T_1)$. The 3P King model fit for $(V - I)$ was consistent for the smaller FOV, but the tidal radius was harder to limit without more data away from the center of Seg 3. Our completeness limits are $T_1 \approx 23.1$ for the Washington CMD and $g \approx 21.8$ for the $(g - r)$ CMD (worse than DR13), but this was because we required at least a $5\sigma$ detection in $u$-band. From 75 runs of the ASteCA code in all colors, iterating toward agreement between the O13, Washington, and SDSS CMDs, the Padova/PARSEC12 solar-scaled models show that Segue 3 has $Z = 0.006 \pm 0.002$, log(Age) = 9.38 $\pm$ 0.11, $(m - M)_0 = 17.33 \pm 0.08$, $E(B - V) = 0.09 \pm 0.01$, and a binary fraction of 0.36 $\pm$ 0.12. The mass estimate from the King models was quite uncertain, $630 \pm 264 M_\odot$. If we only use runs where we remove the SDSS-identified galaxies, and use the information from F11 on radial-velocity members: $Z = 0.006 \pm 0.001$, log(Age) = 9.42 $\pm$ 0.08, $(m - M)_0 = 17.35 \pm 0.08$, $E(B - V) = 0.09 \pm 0.01$, and a binary fraction of 0.39 $\pm$ 0.05, with a cluster mass of 478 $\pm$ 56 $M_\odot$ for the synthetic CMD generated with these parameters. With $Z = 0.006$ and an age of 2.6$^{+0.6}_{-0.4}$ Gyr, our estimates are younger and more metal-rich than those of O13, derived using the same set of isochrones. Converting metallicity into $[\text{Fe}/\text{H}]$ if the cluster is not $\alpha$-enhanced, and would be $[\text{Fe}/\text{H}] \approx -0.8$, if $[\alpha/\text{Fe}] = +0.4$, which we discuss in the next section.

### 3.2. Dartmouth Models

Table 4 shows a representative sample of the Dartmouth models we used, and examples of how they translate into the metallicity scale, with $Z$, $\alpha$-abundances, and helium or $Y$-variations. For comparison, O13 quote a best-fit Padova/ PARSEC isochrone of $Z = 0.003$ and an age of 3.2 Gyr. The PARSEC12 models are solar-scaled, but the Dartmouth models (Dotter et al. 2008; hereafter D08) can be solar-scaled or have variable $\alpha$-abundances or $Y$-content, but only extend to the helium-flash. Recently, Dotter (2016, hereafter: D16) released solar-scaled models that include all evolutionary stages, which we refer to as the MIST models (MESA Isochrones & Stellar
Tracks; also see Choi et al. (2016). We obtained these models in the Washington and SDSS filter systems for this project.

Figure 7 shows color-color plots for our sample, with Figure 7(a) \((u - r)_b\) versus \((u - g)_b\), and (b) \((C - T_1)\) versus \((u - g)_b\). According to the results reported by Li & Han (2008) on AB-system color pairs, \([u - r]_b\), \([r - K_S]\), \([u - r]_b\), \([i - J]_b\), and \([u - K_S]_b\) are more suitable for constraining stellar population parameters than many others, but we do not have enough good 2MASS detections here below the RGB. The objects with smaller photometric uncertainties cluster with the more metal-rich MIST models, but the results are not conclusive from the color-color plots alone.

In Figure 8(a), the \(M_r\) versus \((u - r)_b\) CMD with the D08 models, object 26 is the likely BS (blue filled triangle), located in the cluster center. The objects within 5\(\sigma\) in color and 7\(\sigma\) in magnitude of the average of the best-fit models \((Y = 0.246,\)
Table 4

| [Fe/H] | [$\alpha$/Fe] | $Y^a$ | $Z^b$ | $Z_0^c$ | $Y$ | $Z$ | $Z_0$ | $Y$ | $Z$ | $Z_0$ |
|--------|---------------|-------|-------|--------|-----|-----|-------|-----|-----|-------|
| −2.5   | 0.0           | 0.245 | 0.00005 | 0.00005 | 0.33 | 0.00005 | 0.00005 | 0.4 | 0.00004 | 0.00004 |
| −2.0   | 0.0           | 0.245 | 0.00017 | 0.00017 | 0.33 | 0.00015 | 0.00015 | 0.4 | 0.00014 | 0.00014 |
| −1.5   | 0.0           | 0.246 | 0.00055 | 0.00055 | 0.33 | 0.00048 | 0.00048 | 0.4 | 0.00043 | 0.00043 |
| −1.0   | 0.0           | 0.248 | 0.00172 | 0.00172 | 0.33 | 0.00153 | 0.00153 | 0.4 | 0.00137 | 0.00137 |
| −0.5   | 0.0           | 0.254 | 0.00537 | 0.00537 | 0.33 | 0.00482 | 0.00482 | 0.4 | 0.00431 | 0.00431 |
| −2.5   | 0.4           | 0.245 | 0.00011 | 0.00006 | 0.33 | 0.00100 | 0.00005 | 0.4 | 0.00009 | 0.00004 |
| −2.0   | 0.4           | 0.246 | 0.00035 | 0.00018 | 0.33 | 0.00310 | 0.00156 | 0.4 | 0.00028 | 0.00014 |
| −1.5   | 0.4           | 0.247 | 0.00111 | 0.00056 | 0.33 | 0.00998 | 0.00050 | 0.4 | 0.00088 | 0.00045 |
| −1.0   | 0.4           | 0.251 | 0.00346 | 0.00176 | 0.33 | 0.00310 | 0.00158 | 0.4 | 0.00278 | 0.00141 |
| −0.5   | 0.4           | 0.262 | 0.01069 | 0.00544 | 0.33 | 0.00970 | 0.00494 | 0.4 | 0.00869 | 0.00400 |

Notes. Models from the Dartmouth Stellar Evolution Database (D08).

$^a$ $Y = 0.245 \pm 1.6Z$.

$^b$ $Z$ = Z-value of matching isochrone in CMD-photometric metallicity that includes $\alpha$-abundances and Y-effects.

$^c$ $Z_0$ = expected Z-value, derived iron abundance from spectroscopy alone.

4. Spectral Energy Distributions

We selected the 14 brightest stars above the MSTO from the MIST sample and plot the SEDs with standard ATLAS9 model fluxes (Castelli & Kurucz 2003; 2004) in Figure 10. The photometry is taken from Tables 2 and 3, using $V$ and $I$ from O13, and $z$ from SDSS DR13. The temperature and surface gravity are estimated from an average of the D08 and D16 models, allowing for either [Fe/H] = −0.5 or [Fe/H] = −1.5. All the red models are for [Fe/H] = −0.5 and [$\alpha$/Fe] = 0.0. The blue models are for [Fe/H] = −1.5 and [$\alpha$/Fe] = +0.4, scaled to the same peak flux density. Stars confirmed as $V_r$ members have an asterisk after their identification numbers. Figure 10(a) shows $0.2 < \lambda < 1.0 \mu m$ and
Figure 10(b) displays $0.3 < \lambda < 0.5 \mu m$. Star 26, the suspected BS, is too hot for the low-resolution ATLAS9 models to show a great difference in the metallicity-sensitive $\alpha$- and $C$-bands. The stars between the MSTO and the base of the RGB, objects 205, 143, 100, and 71 are also too hot to show a great difference in the UV-bands. However, all stars brighter than $6^{\circ}$ on the RGB/AGB appear to favor the more metal-rich models. Object 273 is the only source that shows variability between O13, SDSS DR13, and our photometry, and it is located near the (metal-rich) red horizontal branch. All O13 $V$- and $I$-photometry points are surrounded by a blue square, and the $z$ mag is from DR13.

The three most luminous possible members, objects 47, 165, and 86, are separated from the rest of the RGB/SGB MIST sample and could be AGB/HB stars. With $\sim 40\%$ binaries, this cluster could very well have evolved massive BS, but an argument against this interpretation is that they are not in the core of the cluster. Their SEDs do appear to be better fit by the metal-rich models, but these stars require radial-velocity measurements and are bright enough for higher resolution spectral analysis if they are confirmed as members of Segue 3.

5. Age Spread versus Rotation Range

The statistical uncertainties in the photometry at the MSTO should not be large enough to mimic an age spread of $>0.5$ Gyr. O13 compared the Padova and Yale (Demarque et al. 2004) isochrones and concluded that their final uncertainty on the age of Segue 3 was around $\pm 0.5$ Gyr with a maximum age of 4.5 Gyr in the $(V-I)$ data, with a mean of 3.2 Gyr. From the Padova models, with multiple colors to consider and internal and systematic uncertainties, the best fits we can achieve only limit the MSTO age to $2.6^{+0.5}_{-1.0}$ Gyr at $Z = 0.006 \pm 0.002$. For the 49 objects in the MIST selection, the quartile analysis gives $2.2^{+0.6}_{-1.2}$ Gyr for $Z = 0.004 \pm 0.001$, where both the MIST and Padova models are solar-scaled. For the D08 models, with $\alpha$-abundances and helium content allowed to vary, the [Fe/H] grid was coarser: the metallicity distribution peaks at $Z = 0.003 \pm 0.002$, [Fe/H] = $-0.8 \pm 0.4$, with the median being $-0.99$ and the mode $-0.5$. For the same 49 stars, $[\alpha/Fe] = +0.14 \pm 0.15$, so we can justify using the solar-scaled models. Interestingly, $Y = 0.30 \pm 0.06$ from D08.
5.1. Helium Abundances and Stellar Ages with BASE-9

We turned to a different Bayesian-analysis code to reduce systematic uncertainties and handle possible helium-abundance variations. BASE-9 is a Bayesian modeling code that fits cluster parameters for GCs that differ in helium abundance (Stenning et al. 2016), using the $Y$-enhanced Dartmouth isochrones (D08). The BASE-9 code requires prior removal of the field-star population.

We would expect that for a constant [Fe/H], increasing the $\alpha$-abundance causes the evolutionary tracks to appear fainter and redder than in solar-scaled models (increasing $Z$). If a GC population exhibits differences in $Y$ and other light elements (CNO), the effect should be detectable in UV CMDs (Wagner-Kaiser et al. 2016b). As sources of the $Y$-variation in GCs, Wagner-Kaiser et al. (2016b) discuss AGB stars, fast-rotating massive stars, or pre-main sequence disk-pollution (Decressin et al. 2007; D’Antona et al. 2014), all of which might be expected to operate in a GC environment. In contrast, Vandenberg et al. (2012) found that the strongest effect on the isochrones was produced by Mg and Si. We can make a direct comparison by requiring the total abundance of heavy elements to be the same value. For an individual star, increasing $Y$ would shorten the main-sequence lifetime because the rate of H-burning increases (Vandenberg et al. 2012).

Wagner-Kaiser et al. (2016b) investigated 30 GCs from archival HST data in F275W, F336W, and F438W. Of their sample, three clusters have [Fe/H] $\approx -0.7$ to $-0.8$: NGC6624, NGC6637, and NGC6838, with log(Age) = 9.96, 9.98, and 10.01. The first two clusters have DM $\approx 15.3$ and NGC6838 has $DM=13.4$. When we fixed the [Fe/H] value (Wagner-Kaiser et al. 2016b), two populations differing in $Y$-values were found for each system: NGC6624 has $Y_A = 0.265^{+0.001}_{-0.002}$ and $Y_B = 0.343 \pm 0.002$; NGC6637 has $Y_A = 0.265 \pm 0.001$ and $Y_B = 0.330 \pm 0.000$; NGC6838 has $Y_A = 0.301 \pm 0.003$ and $Y_B = 0.341^{+0.004}_{-0.002}$. The proportion of Population A stars (lower $Y$ value) is $\sim 0.25$ for NGC6624 and NGC6637, and $\sim 0.4$ for NGC6838. The more metal-rich clusters in the Wagner-Kaiser et al. (2016b) sample tend to have a smaller range in $Y$ values, and in these HST filters, the RGB positions are shown to be displaced by increasing $\Delta Y$ in their CMDs. In general, the inner MWG GCs tend to have a higher proportion of Population A stars than those in the outer MW over the whole metallicity range of $-2.37 < [Fe/H] < -0.70$ in this sample.

For the Segue 3 data set, we prepared input files for the BASE-9 program (von Hippel et al. 2014; Stenning et al. 2016; Wagner-Kaiser et al. 2016a), using the statistical cleaning provided by ASteCA, the F11 radial velocities, and the MIST selection. We ran BASE-9 for the SDSS and Washington colors and found no strong evidence of a multiple population differing in $Y$ abundance, with the code not settling down and giving two distinct values. When we did not restrict the input parameter ranges in any way, the SDSS colors matched the Padova model output from ASteCA reasonably well. The 90% confidence levels gave a range of $9.42 < \log(Age) < 9.57$, $-0.64 < [Fe/H] < -0.45$, $17.14 < (m-M)_0 < 17.24$, $0.32 < A_V < 0.35$, and $0.25 < Y < 0.29$. However, the Washington colors gave $9.04 < \log(Age) < 9.10$, $-0.54 < [Fe/H] < -0.47$, $18.31 < (m-M)_0 < 18.57$, $0.29 < A_V < 0.32$, and $0.25 < Y < 0.28$. The Washington colors are more sensitive to metallicity, but there is also a stronger degeneracy effect between age, distance, and visual extinction, so the extinction had to be set manually and was not allowed to vary. However, if we set the distance modulus and $E(B-V)$ to the O13 values, the SDSS colors show an interesting effect in BASE-9: there is no abnormal double-$Y$ population, but there seems to be a double peak in age, with $-0.89 < [Fe/H] < -0.69$, as shown in Figure 11. The SDSS colors yield $Y = 0.27 \pm 0.02$, but imply an age spread of $\sim 0.4$ Gyr, where the two peaks are clearly resolved in Figure 11 and the log(Age) resolution is better than 0.1 dex.

5.2. Rotation at the Turnoff

In neither the Padova and Dartmouth models, with “chi-by-eye” and Bayesian statistics, can we force the age-distribution uncertainty at the MSTO much below a range of $\pm 0.5$ Gyr. The narrow SGB would normally preclude any age spread and should argue against any multiple population in Segue 3, characteristic of the ancient MW GC population (Gratton et al. 2012). Certainly, Segue 3 shows the effect of a large proportion of binaries in the core ($\approx 40\%$), but the luminosity spread at the MSTO could also be the effects of rotation (Li et al. 2012; Piatti & Bastian 2016).

The closest comparison cluster to Segue 3 in age and metallicity and the shape of the MSTO (admittedly, a much more massive system) can be found in the Small Magellanic Cloud (SMC). Li et al. (2014) studied NGC 1651, an intermediate-age massive cluster. NGC 1651 had exhibited a supposed age spread at the MSTO, but Li et al. (2014) explained the extended MSTO by stellar rotation variations. Later, Li et al. (2015) updated their work and found that the best fit to the observed CMD involved a period of extended star formation that resulted in population ages...
from 1.4 to 1.8 Gyr. This comprised 50% binaries and 70% stars with enhanced rotation.

In Figure 12(a) we show the \( V_r \) members and the Hertzsprung-Russell diagram of the MIST selected sample, using the D08 and D16 models (model fits listed in Table 5), where we number the stars from Figure 10. The cyan/black track is the best fit to the MSTO, and the SGB is best fit by the red track with \( Y = 0.254 \), \([\text{Fe/H}] = -0.5\), \([\alpha/\text{Fe}] = 0.0\), and 2.5 Gyr, \( \Omega/\Omega_{\text{crit}} = 0.4 \) (all the MIST models are set to that average rotation here). The F11 confirmed members at the MSTO have a mass of \( \approx1.3M_\odot \), in agreement with O13; the unconfirmed post-SGB objects could be more massive only if they are evolved BSs, not if they are normal post-MS stars. The Dartmouth models cover the Segue 3 (confirmed) mass range from the upper-MS to the SGB, \( M = 0.7 - 1.5M_\odot \) (with a BS estimated mass of \( \approx2.7M_\odot \)). Figure 12(b) is adapted from Li et al. (2014) and Georgy et al. (2013), showing Geneva models for a cluster of the same approximate age and metallicity (NGC 1651 and Segue 3) with the full range of rotation rates, mass tracks for \( M = 1.7M_\odot \) are shown. Figure 12(c) shows a full range of models for a 2.0\( M_\odot \) star. In Figure 12(b), just at the jump between the MSTO and SGB, the difference of 0.04 dex in \( \log T_{\text{eff}} \) translates into about 0.5 Gyr in an apparent age difference for the stars, but this can also indicate the difference between a non-rotating star and a turnoff star that is rotating almost at breakup. This is the clearest result of a spread in rotation but not age, causing the somewhat braided appearance of the MSTO in \((C-T_1)\) (Figure 8(c)). We conclude that the MSTO morphology is likely to be a combination of rotational effects and the high fraction of binaries because the SGB is too narrow to allow for multiple populations, at least among the stars that remain in the core of Segue 3. The YMCs studied by Li et al. (2016) in the LMC, NGC 1831, NGC 1868, and NGC 2249, appear to have multiple populations and could show age spreads and broader SGBs, but are all younger than 1.5 Gyr. Examining the MSTO in Figure 8(c) compared to Figure 12(a), the isochrone fit has rejected what would have been the slow rotators—as we can see from the models in Figures 12(b) and 12(c). Since we recovered 19/27 F11 objects and most of those non-recovered were bluer than the MIST \( \Omega/\Omega_{\text{crit}} = 0.4 \) isochrone, we surmise that \( \sim70\% \) of the Segue 3 stars have enhanced rotation (leaving 30% with little or no rotation), in a cluster with \( \sim40\% \) of the stars being binaries, which is similar to NGC 1651 (Li et al. 2015).

The Geneva online database can calculate a coarse grid of models for two rotation rates (zero and \( \Omega/\Omega_{\text{crit}} = 0.568 \)) for \( Z = 0.002 \), which would correspond to \([\text{Fe/H}] = -0.9\) and \([\alpha/\text{Fe}] = +0.4\) on the D08 scale. When we examined the MSTO masses of the \( V_r \) members against the Geneva models, the non-rotating case gives the TO mass as 1.2\( M_\odot \) and the limit...
of the stars with radial velocities as about 0.7$M_\odot$. The rotating models give these limits as 1.25$M_\odot$ and 0.8$M_\odot$, which is not significantly different from the D08/D16 models. However, the BS mass is higher than in the D08/D16 system. The Geneva models for $Z = 0.002$ can fit the Seg 3 MSTO with an age difference from log(Age) = 9.45–9.5, which is 2.8–3.2 Gyr, or log(Age) = 9.45 with a rotation range of $\Omega/\Omega_{\text{crit}} = 0.95$, but the narrow SGB luminosity implies a younger age for the system. The D08, D16, Padova, and Geneva models generally fit the Segue 3 CMD for $Z = 0.004 \pm 0.002$ and ages of 2–3 Gyr, but the ASteCA code gives us confidence in the uncertainties, rather than a fit-by-eye alone.

To further test the rotation hypothesis on Segue 3 we created model clusters with The Geneva SYnthetic Clusters Isochrones & Stellar Tracks (SYCLIST) code, which can produce synthetic clusters at $Z = 0.014$ and $Z = 0.002$ (Georgy et al. 2013, 2014). We selected the $Z = 0.002$ case and produced models shown in Figure 12(d) and (e) for the appropriate ages.

Georgy et al. (2014) illustrated that for clusters with a metallicity $Z = 0.002$–0.014 and an age range of 0.030–1 Gyr, the SYCLIST models show that the largest proportion of fast rotators on the MS exist just below the turnoff. This happens because rotation extends the MS lifetime compared to non-rotating models, whereas helium enhancement reduces it, and the fraction of fast rotators one magnitude below the turnoff also increases with the age of the cluster between 30 Myr and 1 Gyr. Our best estimates for the $(C - T_l)$ CMD (see Figure 8(c)) fit with the D16/MIST models give $Y = 0.256$, $[\text{Fe}/\text{H}] = -0.5$, $[\alpha/\text{Fe}] = 0.0$, 2.0–3.2 Gyr, and $\Omega/\Omega_{\text{crit}} = 0.4$. For the stars that are about 1 mag below the MSTO, the stars to the far red side of the MS are a clear binary sequence and the stars to the far blue side could be faster rotators instead of $Y \sim 0.3$ (D08 models). This effect is most obvious in the Washington system. Brandt & Huang (2015) also discussed MESA (which we call D16/MIST) rotating models in relation to CMDs for LMC clusters, showing examples of the broad MSTOs reaching a maximum extent for cluster-ages of 1–1.5 Gyr and tailing off by ~2 Gyr, where the models show this in Figure 12(c) (Georgy et al. 2013) for 2$M_\odot$ stars. The shape of the Seg 3 MSTO/SGB in Washington colors compared to the MIST isochrones and SYCLIST models places a lower limit on the age of the Seg 3 cluster at 2 Gyr, but implies a range of rotation rates. The models generated in Figures 12(d) and (e) for log(Age) = 9.5 and 9.45 (light blue and gold, respectively) indicate that the Seg 3 SGB stars are probably younger than 3.0 Gyrs.

6. Age versus Metallicity

The implied split at the MSTO is more likely due to a difference in rotation rates and binarity, not age, where this conclusion is supported by the narrow SGB. The age and metallicity of Segue 3 resemble a very sparse disrupted version of the SMC cluster, NGC 1651 (Li et al. 2014), and other comparisons would be the outer LMC clusters, KMHK 1751 and 1754 (Piatti & Bastian 2016).

It is possible, but unlikely, that $[\text{Fe}/\text{H}]$ appears higher than −1 because of CN enhancement (Cummings et al. 2017). However, the drift toward higher Z is detected in all filters, including $(V - I)$, when we use the ASteCA code to remove user bias.

Figure 13 compares MW GC data with the clusters in some nearby dwarf galaxies (Leaman et al. 2013a, and references therein). We show the age-metallicity relationship (AMR) for the MW GCs and Leaman et al. (2013b) presented models for the WLM, SMC, and LMC dwarf galaxies are shown (and extrapolated in the yellow window inset). Some newer halo clusters are denoted as black squares. A representation of the AMR of the MW bulge GCs is shown as the dashed region. We combined the VandenBerg et al. (2013) data on 55 MW GCs, identified by red ($R_C < 8$ kpc) and blue ($R_C > 8$ kpc)—separating clusters by their distance from the galactic center ($R_C$). The Harris (1996) data are more comprehensive, but the VandenBerg et al. (2013) data are more uniform. The newer halo globulars discussed in O13 are added to the HST GC, with Ko 1 and 2 from Paust et al. (2014), which they identified as OCs. The red open squares are LMC clusters, and the orange open triangles are the SMC clusters used by Piatti et al. (2002). The F11 data point is shown as a blue square with a red border. This study’s result is shown as a magenta triangle for the Padova/ASteCA fit. Our results indicate that Segue 3 resembles the LMC clusters, and we support O13’s claim that it is the youngest globular-like cluster in the MW, although spectroscopy is needed to confirm its nature, if we are to rule out that it could be an old sparse OC. In either case, its location in the outer halo and its youth argue against it being a cluster native to our Galaxy.

Aller & Greenstein (1960) noted the $\alpha$–element enhancement in metal-poor stars compared to the solar value more than fifty years ago, and Wallerstein (1962) decisively found excesses of Mg, Si, Ca, and Ti relative to Fe. Typically, GC stars show $[\alpha/\text{Fe}]$ of around +0.4, but non-cluster halo stars show more scatter in this parameter, where Feltzing & Chiba (2013, and references therein) gave a recent review including MW disk(s), bulge, and halo. At low metallicity, $[\text{Fe}/\text{H}]$ does not necessarily scale linearly with $[\text{Ca}/\text{H}]$ or $[\text{Ca}/\text{Fe}]$ (Anthony-Twarog & Twarog 1998). Tests with the D08 and D16 models showed that the Seg 3 population is not significantly $\alpha$-enhanced. The stellar populations from the LMC and Sgr dSph have a different enrichment knee.
Figure 12. (a) Translating the CMD into the log \(L(L_\odot)\) vs. log \(T_{\text{eff}}\) plane for the D08 and D16/MIST models, the cyan/black track is the best mean fit to the MSTO stars from F11 (red filled circles). We show the Dartmouth models for the Seg 3 mass range from the MS to the SGB, \(M = 0.7-1.5 M_\odot\), with the 49 brighter probable members shown as open red triangles. We number the 14 stars from Figure 10, and these always appear in the same order in the rest of Figure 12. (b) From Li et al. (2014) and Georgy et al. (2013), Geneva models for a model cluster of the same approximate age and metallicity with the full range of rotation rates, mass tracks for \(M = 1.7 M_\odot\) are shown. (c) From Georgy et al. (2013), mass tracks for \(M = 2.0 M_\odot\) are shown for a range of rotation rates. (d) Geneva model clusters with 250 stars with \(Z = 0.002\), with non-rotating models with log(Age) = 9.45 and 9.5 (light blue open circles and gold circles, respectively), and (e) the same Segue 3 stars as open red triangles, with \(\Omega/\Omega_{\text{crit}} = 0.568\) models with log(Age) = 9.45, on the mass tracks with rotation from Georgy et al. (2013).

Table 5

| ID | log(Age) | \(Z\) | log \(T_{\text{eff}}\) | log \(L/L_\odot\) | log \(g\) | \(M/M_\odot\) | Comments |
|----|----------|------|-----------------|-----------------|---------|-----------------|----------|
| 6a | 6.00     | 0.0045 | 3.718           | 1.113           | 3.464   | 2.043           | Brightest SGB |
| 26 | 8.25     | 0.0045 | 4.095           | 1.887           | 4.304   | 2.609           | Possible BS |
| 47 | 8.70     | 0.0046 | 3.720           | 2.271           | 2.419   | 2.623           | Brightest Post-MS |
| 71a| 8.40     | 0.0045 | 3.776           | 1.055           | 3.727   | 1.934           | SGB |
| 86 | 9.35     | 0.0046 | 3.694           | 1.912           | 2.415   | 1.474           | SGB |
| 100 | 9.40  | 0.0042 | 3.833           | 1.058           | 3.792   | 1.335           | Post-MS |
| 101 | 9.25   | 0.0045 | 3.712           | 1.130           | 3.324   | 1.522           | RGB/SGB |
| 108 | 5.15   | 0.0045 | 3.698           | 1.311           | 3.093   | 1.652           | RGB |
| 134 | 9.45   | 0.0045 | 3.706           | 1.241           | 3.100   | 1.3301          | SGB |
| 143a| 9.40   | 0.0042 | 3.837           | 1.052           | 3.812   | 1.330           | SGB |
| 150a| 9.35   | 0.0041 | 3.852           | 0.868           | 4.054   | 1.322           | SGB |
| 165 | 9.00   | 0.0046 | 3.689           | 2.111           | 2.354   | 2.073           | Post-MS |
| 205a| 9.30   | 0.0042 | 3.8656          | 0.889           | 4.097   | 1.349           | MISTO |
| 273 | 9.20   | 0.0046 | 3.699           | 1.577           | 2.818   | 1.603           | Post-MS—Variable? |

Notes. Models D16/MIST. We restricted the distance modulus and extinction from our Padova fits and let \(Z = 0.006 \pm 0.002\), with no restriction on age.

a Identified by \(V_r\) in F11.

b Young age estimate. BS or evolved BS?

t (Venn et al. 2004), the metallicity where chemical enrichment of the environment changes from SN Type II to Ia.

The cluster Palomar 1 (Sarajedini et al. 2007; Sakari et al. 2011) fits the AMR for the LMC in Figure 13. The AMR for GCs is quite different for the MW Halo and bulge, but Segue 3 does not even fit in with unusual clusters that were likely acquired from non-MW sources.

When Paust et al. (2014) calculated the tidal radius of Ko 1 and 2, they used \(r_t = R_G C(2(M_C/M_{\text{MBW}}))^2\), which yields \(r_t = 24 \pm 5\) pc considering mass and distance uncertainties. The King model of Figure 1 for the the highest mass for Segue 3 from the ASteCa runs gives \(r_t \approx 20 \pm 10\) pc. The uncertainty in the King model fit results from fitting a sparse-cluster radial density profile, where the cluster is not spherical.

7. Summary and Conclusions

The mean position of the Segue 3 center in all filters is R.A. = 320°38015 and decl. = 19°11753. From cluster-cleaning and background subtraction experiments, fitting a 3P King model yields a cluster radius of \(r_c = 0.017 \pm 0.007\), the core radius is \(r_c = 0.003 \pm 0.001\), and the tidal radius is likely to be...
Figure 13. Combination of the VandenBerg et al. (2013) (uniform) data on 55 MW GCs, identified by red ($R_C < 8$ kpc) and blue ($R_C > 8$ kpc)—separating clusters by their distance from the galactic center ($R_C$). The newer halo globulars discussed in O13 are added to the HST GC, with Ko 1 and 2 from Paust et al. (2014, which they identified as OCs). The red open squares are LMC clusters, and the orange open triangles are the SMC clusters used by Piatti et al. (2002). The F11 data point is shown as a blue filled square with a red border. NGC 1651 is shown as a red filled square. The Leaman et al. (2013a, 2013b, and references therein) models for the AMRs for the WLM, SMC, and LMC dwarf galaxies are shown (extrapolated in the yellow-tinted window) and six newer halo clusters are noted as black squares. A representation of the age-metallicity relationship of the MW bulge GCs is shown as the dashed region. NGC 1651 (Li et al. 2014) is located just below the Segue 3 Padova result, which belongs to the LMC.

Table 6
Final Results from All Models

| Models  | Method   | Filters          | logAge  | Z       | [$\alpha$/Fe] | $(m - M)_B$ | $E(B - V)$ | Notes          |
|---------|----------|------------------|---------|---------|---------------|-------------|------------|----------------|
| Padova  | ASteCA   | VI               | 9.40 ± 0.2 | 0.007 ± 0.002 | 0.0 | 17.36 ± 0.03 | 0.09 ± 0.01 | O13; 1 runb, VI only |
| Padova  | ASteCA   | SDSS − gr        | 9.5 ± 0.2 | 0.002 ± 0.003 | 0.0 | 17.37 ± 0.03 | 0.09 ± 0.01 | 1 runb          |
| Padova  | ASteCA   | CT_{ugr}VI       | 9.38 ± 0.11 | 0.006 ± 0.002 | 0.0 | 17.33 ± 0.08 | 0.09 ± 0.01 | Multi. runs       |
| Padova  | ASteCA   | CT_{ugr}VI       | 9.42 ± 0.08 | 0.006 ± 0.001 | 0.0 | 17.35 ± 0.08 | 0.09 ± 0.01 | Multi. runs       |
| D08     | BASE-9   | $C_{\text{Lab}}$ | 9.51±0.14 | 0.005 ± 0.001 | 0.0 | 17.18±0.06 | 0.11 ± 0.01 | $Y = 0.27 ± 0.02$ | a, c |
| D08     | Manual   | $C_{\text{Lab}}$ | 9.35±0.10 | 0.006 ± 0.003 | 0.14 ± 0.15 | 17.33a | 0.09 | $Y = 0.30 ± 0.06$ | a, e |
| MIST    | Manual   | $CT_1$           | 9.35±0.10 | 0.004 ± 0.001 | 0.0 | 17.33a | 0.09 | $Y = 0.245 ± 0.06$ | h |
| Geneva  | Manual   | $CT_1$           | 9.4 ± 0.1  | 0.002b   | 0.0 | 17.33a | 0.09 | $Y = 0.248$     |

Notes. Model control:

a Set to 0.09 or only allowed to vary between 0.05–0.15.
b “Automatic” mode, mid-range membership and cluster radius.
c Semi-automatic mode, varying membership stringency and cluster-size determination.
d 49 stars.
e Variable helium content.
f “Manual’’ $\chi^2$-fit to model grid.
g Set to best average/O13 value.
h $Y$ set by $Z$.
i The only metal-poor Geneva model with variable rotation used.

$\eta = 0.04 ± 0.02$. From all runs of the ASteCA code, iterating toward agreement between the O13, Washington, and SDSS CMDs, the Padova/PARSEC12 solar-scaled models show that Segue 3 has $Z = 0.006 ± 0.002$, log(Age) = 9.38 ± 0.11, $(m - M)_B = 17.33 ± 0.08$, $E(B - V) = 0.09 ± 0.01$, with a binary fraction of 0.36 ± 0.12. The mass estimate from the King models was quite uncertain, 630 ± 264 $M_\odot$. When we only use the runs where we removed the SDSS-identified galaxies and use the information from F11 on radial-velocity members, $Z = 0.006 ± 0.001$, log(Age) = 9.42 ± 0.08, $(m - M)_B = 17.35 ± 0.08$, and $E(B - V) = 0.09 ± 0.01$, with a binary fraction of 0.39 ± 0.05, giving a cluster mass of 478 ± 56 $M_\odot$. With $Z = 0.006$ and an age of 2.6$^{+0.6}_{-0.4}$ Gyr, our estimates for Segue 3 are younger and more metal-rich than the result of
O13 obtained using the same set of isochrones. Converting metallicity into iron abundance yields \( [\text{Fe}/\text{H}] \approx -0.5 \) if the cluster is not \( \alpha \)-enhanced, and \( [\text{Fe}/\text{H}] < -0.5 \) if \( [\alpha/\text{Fe}] \) is positive. Seg 3 does not follow the AMR trend of MW-native GCs, resembling field stars and clusters from the (gas-rich) WLM dIrr, SMC, and LMC. Comparing the GC data with Leaman et al. (2013a, 2013b) models indicates that a system with the Segue 3 properties could have been formed in an LMC/SMC-like system when we extrapolate their “leaky box” models. The results of this paper are summarized in Table 6.

We confirm the results of O13: Segue 3 is certainly the youngest GC found in the MW to date, and it was more massive in the past. Our results favor Segue 3 being a disrupting GC and not an OC. When we reanalyzed the O13 data using the ASteCA code, the results for the distance modulus were consistent with the Washington and SDSS analysis, but the SDSS colors are less sensitive to \( E(B-V) \) than the Washington colors. However, the broader \( C \)-filter allowed us to go deeper than \( u \)-band. Our analysis shows the importance of comparing clusters within the same model grid. The D16/MIST models (although solar-scaled) are more useful for estimates of the age uncertainty in Washington colors because of the finer grid and the extension of the models past the helium flash. The D08 models include a range of \( \alpha \) abundances and \( Y \) values that are used with BASE-9 (Wagner-Kaiser et al. 2016a, 2016b): for a single-population model, Seg 3 has \( Y = 0.27 \pm 0.02 \), but this might be a rotation effect that causes stars to be bluer below the MSTO.

Although unusual, Segue 3 is not unique in being a young metal-rich cluster in the MW outer halo (see Figure 13). Other such clusters have been found in the MW, including those assumed to be associated with the Sgr dSph (Cohen 2004; Sbordone et al. 2005; Law & Majewski 2010, for Pal 12, Ter 7, and Whiting 1, respectively). Other MW clusters are of similarly low mass and fall somewhere between traditional open and GCs (Sakari et al. 2011, e.g., Pal 1) or seem to be massive old open clusters (Paust et al. 2014, who studied Ko 1 and 2). Indeed, Pal 12, Ter 7, and Pal 1 all show low \( [\alpha/\text{Fe}] \) abundances (Cohen 2004; Sbordone et al. 2005; Law & Majewski 2010) typical of dwarf galaxy stars (Tolstoy et al. 2009), which do not follow the standard MW \( \alpha \) enhancement (Aller & Greenstein 1960; Wallerstein 1962). Tests with D08 and D16 models suggest that Segue 3 is not significantly \( \alpha \) enhanced, but a firm conclusion requires spectroscopic follow-up. However, there is circumstantial evidence that Segue 3 came from an accreted gas-rich system (Belokurov et al. 2007, B10, F11, O13).

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Facility: APO: 3.5 m.
Software: IRAF, Python, ASteCA, BASE-9, SYCLIST.

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