THE SEGUE STELLAR PARAMETER PIPELINE. II. VALIDATION WITH GLOBULAR
AND OPEN CLUSTERS

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ABSTRACT

We validate the accuracy and precision of the current SEGUE (Sloan Extension for Galactic Understanding and Exploration) Stellar Parameter Pipeline (SSPP), which determines stellar atmospheric parameters (effective temperature, surface gravity, and metallicity) and radial velocities (RVs), by comparing these estimates for selected members of three globular clusters (M 13, M 15, and M 2) and two open clusters (NGC 2420 and M 67) to the literature values. Spectroscopic and photometric data obtained during the course of the original Sloan Digital Sky Survey (SDSS-I) and its first extension (SDSS-II/SEGUE) are used to determine atmospheric parameter and RV estimates for stars in these clusters. Based on the scatter in the metallicities derived for the members of each cluster, we quantify the typical uncertainty of the SSPP values, \( \sigma([Fe/H]) = 0.13 \text{ dex} \) for stars in the range of \(-0.3 \leq g-r \leq 1.3\) and \(2.0 \leq \log g \leq 5.0\), at least over the metallicity interval spanned by the clusters studied \((-2.3 \leq [Fe/H] \leq 0.0\)). The surface gravities and effective temperatures derived by the SSPP are also compared with those estimated from the comparison of color–magnitude diagrams with stellar evolution models; we find satisfactory agreement \((\sigma(T_{\text{eff}}) < 200 \text{ K} \text{ and } \sigma(\log g) \leq 0.4 \text{ dex})\).

Key words: methods: data analysis – stars: abundances – stars: fundamental parameters – surveys – techniques: spectroscopic

Online-only material: color figures, machine-readable and VO tables

1. INTRODUCTION

The Sloan Extension for Galactic Understanding and Exploration (SEGUE) is one of the three key projects (LEGACY, SUPERNOVA SURVEY, and SEGUE) in the recently completed first extension of the Sloan Digital Sky Survey, known collectively as SDSS-II. The SEGUE program obtained ugri\(z\) imaging of some 3500 deg\(^2\) of sky outside of the SDSS-I footprint (Fukugita et al. 1996; Gunn et al. 1998, 2006; York et al. 2000; Stoughton et al. 2002; Abazajian et al. 2003, 2004, 2005; Pier et al. 2003; Adelman-McCarthy et al. 2006, 2007, 2008), with special attention being given to scans of lower Galactic latitudes \((|b| < 35^\circ)\) in order to better probe the disk/halo interface of the Milky Way. SEGUE also obtained \(R \approx 2000\) spectroscopy over the wavelength range 3800–9200 Å for some 250,000 stars in 200 selected areas over the sky available from Apache Point, New Mexico.

The SEGUE Stellar Parameter Pipeline (hereafter, SSPP) processes the wavelength- and flux-calibrated spectra generated by the standard SDSS spectroscopic reduction pipeline (Stoughton et al. 2002), obtains equivalent widths and/or line indices for 82 atomic or molecular absorption lines, and estimates \(T_{\text{eff}}, \log g, \text{ and } [Fe/H]\) through the application of a number of approaches. The current techniques employed by the SSPP include a minimum distance method (Allende Prieto et al. 2006), neural network analysis (Bailer-Jones 2000; Willemsen et al. 2005; Re Fiorentin et al. 2007), autocorrelation analysis (Beers et al. 1999), and a variety of line index calculations based on previous calibrations with respect to known standard stars (Beers et al. 1999; Cenarro et al. 2001a, 2001b; Morrison et al. 2003). The SSPP employs six primary methods for the estimation of \(T_{\text{eff}}, \) ten for the estimation of \(\log g, \) and 12 for the estimation of \([Fe/H].\) Details of the methods used are discussed by Lee et al. (2008, hereafter Paper I). The use of multiple methods allows for empirical determinations of the internal errors for each parameter, based on the range of reported values—typical internal errors for stars in the temperature range 4500 K \(< T_{\text{eff}} < 7500 \text{ K} \approx 70 \text{ K, } \sim 0.18 \text{ dex, and } \sim 0.10 \text{ dex, in } T_{\text{eff}}, \log g, \text{ and } [Fe/H], \) respectively. Allende Prieto et al. (2008, hereafter Paper III) point out that the internal uncertainties provided by the SSPP underestimate the typical random errors at high signal-to-noise ratios (S/Ns), because most methods in the SSPP make use of similar
parameter indicators (e.g., hydrogen lines for effective temperature) and similar atmospheric models. Paper III empirically determines external uncertainties of $\sim 130$ K, $\sim 0.21$ dex, and $\sim 0.11$ dex, for $T_{\text{eff}}$, log $g$, and [Fe/H], respectively, by comparison with high-resolution spectroscopy ($7000 < R < 45,000$) of brighter SDSS-I/SEGUE stars that have been obtained with 8–10 m class telescopes. Somewhat larger errors apply to stars with temperatures near the extremes of the range above. The present study of Galactic globular and open cluster stars tests the SSPP’s ability to derive accurate results for stars with a wide range of temperatures and gravities appropriate for metal-poor and near-solar-metallicity stellar populations in the Galaxy, and demonstrates that the derived metallicity scale is identical for dwarfs and giants.

Although the SSPP will continue to evolve in the near future, it has been frozen for now at the version used for obtaining results for stars with suitable data from SDSS Data Release 6 (DR-6; Adelman-McCarthy et al. 2008). Previous versions of the SSPP have already been used for the analysis of SDSS-I observations. For example, Allende Prieto et al. (2006) report on the application of one of the methods included in the SSPP to some 20,000 F- and G-type stars from SDSS-I DR-3 (Abazajian et al. 2005). Beers et al. (2006) have compiled a list of over 6000 stars with [Fe/H] < $-2.0$ (including several hundred with [Fe/H] < $-3.0$), based on the application of the present SSPP to some 200,000 stars from SDSS-I DR-5 (Adelman-McCarthy et al. 2007). Carollo et al. (2007) report on an analysis of the kinematics of relatively bright stars from SDSS-I that have been used as calibration objects during the main survey.

In this paper, the second in the SSPP series, we show that estimates of the atmospheric parameters and radial velocities (RVs) obtained by the SSPP for stars with a reasonable likelihood of membership in previously studied Galactic globular and open clusters are sufficiently accurate to justify the use of the present SSPP parameters for carrying out detailed studies of the halo and thick-disc populations of the Milky Way. In deriving the overall iron abundance for each cluster, we assume that each individual cluster comprises a chemically homogeneous population.

This paper is organized as follows. In Section 2, the photometric and spectroscopic data obtained for M13, M15, M2, NGC 2420, and M67 are described. Section 3 presents the methods used to separate likely cluster members from field stars in the directions toward these clusters. Best estimates of the overall [Fe/H] and RV of selected true members of each cluster are derived in Section 4. A comparison of the determined [Fe/H] and RV with previous studies is discussed in Section 5. In Section 6, we compare the SSPP determinations of $T_{\text{eff}}$ and log $g$ for selected member stars in each cluster with their expected positions on color–magnitude diagrams (CMDs). A summary and brief conclusions are provided in Section 7.

2. PHOTOMETRIC AND SPECTROSCOPIC DATA

Galactic globular and open clusters are nearly ideal testbeds for the validation of the stellar atmospheric parameters estimated by the SSPP. In most clusters, it is expected that their member stars were born simultaneously out of well-mixed, uniform-abundance gas at the same location in the Galaxy. Therefore, with the exception of effects due to post-main-sequence (post-MS) evolution, primordial variations in carbon and nitrogen, or contamination from binary companions that have transferred material, the member stars should exhibit very similar elemental abundance patterns. Three of the clusters in our study—M13, M15, and M2—have well-known CN variations that extend to the MS turnoffs (TOs; Smith & Briley 2006 for M13; Cohen et al. 2005 for M15; Smith & Mateo 1990 for M2). However, these abundance variations can be ignored when deriving metallicities from regions of the spectra that do not include CH, CN, or NH features, as is the case with most of our techniques (those that may be affected by the presence of such features are automatically de-selected in the determination of the adopted [Fe/H]).

True cluster members should exhibit small RV differences with respect to their parent clusters. Furthermore, it is possible to examine theoretical predictions of temperatures and surface gravities for member stars that lie along the cluster MS, red giant branch (RGB), or horizontal branch (HB) in CMDs. As part of tests of the SEGUE star-selection algorithm (Adelman-McCarthy et al. 2008) and the SSPP, and during normal SEGUE operation, we have obtained $ugriz$ photometry and medium-resolution ($R \sim 2000$) spectroscopy for large numbers of stars along lines of sight toward the globular clusters M13, M15, and M2 and the open clusters NGC 2420 and M67. Below we discuss these photometric and spectroscopic data in more detail.

2.1. Photometric Data

The SDSS obtains scans of the sky using the ARC 2.5 m telescope on Apache Point, New Mexico. These data are collected in five broadbands ($u$, $g$, $r$, $i$, $z$) with central wavelengths 3551, 4686, 6166, 7480, and 8932 Å (Fukugita et al. 1996), respectively, using an imaging array of 30 ($6 \times 6$) 2048 × 2048 Tektronix CCDs (Gunn et al. 1998). The pixel size is 24 μm, corresponding to 0.396 on the sky. A series of software procedures, collectively known as the SDSS PHOTO pipeline (Lupton et al. 2001), processes and reduces the scanned images shortly after data are obtained. As part of these procedures, the instrumental fluxes and astrometric positions (Pier et al. 2003) as well as a determination of whether an object is likely to be stellar (i.e., a point source), or not (an extended source) are obtained. Afterward, the photometric data are further calibrated by matching to brighter known standards observed with a smaller calibration telescope on Apache Point (Hogg et al. 2001; Smith et al. 2002; Tucker et al. 2006). The processed photometric data have been shown to exhibit 2% relative and absolute errors in $g$, $r$, and $i$, and 3–5% errors in $u$ and $z$ for all stellar objects brighter than $g = 20$ (Stoughton et al. 2002; Abazajian et al. 2004, 2005; Ivezić et al. 2004). The first-pass photometric data for each of the clusters used in the present study were secured by querying the DR-3 (Abazajian et al. 2005), DR-5 (Adelman-McCarthy et al. 2007), and DR-6 (Adelman-McCarthy et al. 2008) releases from the SDSS Catalog Archive Server (CAS).

Figure 1 illustrates one of the primary challenges in working with data for clusters obtained with SDSS—the automated PHOTO pipeline (Lupton et al. 2001) was not designed to adequately deal with crowded fields such as the central regions of globular clusters. As a result, essentially all of the stars in this region (which are by definition the most likely ones to be cluster members) do not have reported apparent magnitudes in the SDSS CAS. To circumvent this limitation as much as possible, we have instead performed crowded-field photometry for the center of the clusters, using the DAOPHOT/ALLFRAME suite of programs (Stetson 1987, 1994). A full description of the methods used and the photometric measurements obtained is provided by An et al. (2008). Briefly, DAOPHOT was run on each image, and the five images of each field (one for each filter) were then simultaneously run through ALLFRAME.
HSTDAOGROW, which is a modified version of DAOGROW (Stetson 1990), was used to derive aperture corrections to the point-spread-function photometry for the SDSS aperture radius of 7.4. Finally, the DAOPHOT photometry was tied to the native 2.5 m photometric system, using data in fields farther away from the clusters. This procedure also permits a check on the techniques used by the SDSS PHOTO pipeline in regions outside the cluster where the areal density of sources on the sky is sufficiently low.

After completing the above procedures, we finally combined the results from the PHOTO pipeline with those from the crowded-field photometry to obtain an almost complete catalog of $ugriz$ photometry for stars in the region of each of our program clusters. All photometric data are corrected for extinction and reddening by the application of the Schlegel et al. (1998) maps. The average reddening, $E(B - V)$, for stars in the direction of these clusters is listed in Table 1 along with values from the literature. The agreement with previous reported reddening estimates is quite good, with four of the five clusters lying within 0.015 mag of the literature values. The one exception is M67, for which we obtain a reddening estimate 0.03 mag lower than the literature value. Even this slight disagreement is only marginally larger than the errors in the photometric determinations themselves, and is too small to significantly impact estimates of the stellar parameters for cluster stars. The more detailed photometric analysis of An et al. (2008) adopted very similar values of the reddening as those in Table 1.

### 2.2. Spectroscopic Data

The spectroscopy discussed in the present paper was obtained during the course of SEGUE tests and normal SEGUE observations. In normal SEGUE operation mode, a pair of plug plates (referred to as the “bright” and “faint” plates) are obtained over the 3° field of the ARC 2.5 m. A total of 640 optical fibers are employed to obtain $R = 2000$ spectra for on the order of 600 program stars for each plug plate (the remaining fibers are used for spectrophotometric and reddening calibration objects, and observations of the night sky). The exposure time depends on the observation conditions. For a bright plate, exposures are set to achieve a total $(S/N)^2 > 15/1$ from the two blue-side CCDs on the SDSS spectrographs; the exposure for a faint plate is set such that a total $(S/N)^2 > 50/1$ for all four (red and blue CCDs) on the SDSS spectrographs is achieved. In order to identify and remove cosmic-ray hits, each plug plate must have at least three exposures; the integration time for any single exposure is not longer than 30 minutes. For the purposes of targeting objects on these plug plates, the boundary between the bright and faint plates is set at $r \sim 18.0$. The data thus obtained are processed through the SDSS spectroscopic pipeline software (SPECTRO2D and SPECTRO1D), which produces wavelength- and flux-calibrated spectra, and also obtains

### Table 1: Properties of the Clusters

| Parameter       | M 13  | M 15  | M 2   | NGC 2420 | M 67  |
|-----------------|-------|-------|-------|----------|-------|
| (NGC 6205)      |       |       |       |          |       |
| (NGC 7078)      |       |       |       |          |       |
| (NGC 7089)      |       |       |       |          |       |
| R.A. (J2000)    | 16:41:1.5 | 21:29:58.3 | 21:33:29.3 | 07:38:23 | 08:51:18 |
| Decl. (J2000)   | +36:27:37 | +12:10:01 | +00:49:23  | +21:34:24 | +11:48:00 |
| $(l, b)$        | (59.0, +40.9) | (65.0, −27.3) | (58.4, −35.8) | (198.1, +19.6) | (215.7, +31.9) |
| $[\text{Fe}/\text{H}]$ | −1.54 | −2.26 | −1.62 | −0.44 | +0.02 |
| $m - M$         | 14.48 | 15.37 | 15.49 | 12.54 | 9.97 |
| $V_r$ (km s$^{-1}$) | −245.6 | −107.0 | −0.3 | 75.5 | 32.9 |
| $E(B - V)^a$    | 0.02  | 0.10  | 0.06 | 0.03 | 0.06 |
| $E(B - V)^b$    | 0.017 | 0.110 | 0.045 | 0.041 | 0.032 |
| $r_1$           | 25.18 | 21.50 | 21.45 | 5c | 25c |

Notes. The parameter $r_1$ is the tidal radius in arcminutes (except where noted above). The listed distance modulus, $m - M$, is corrected for extinction. The parameters for the globular clusters, M 13, M 15, and M 2, are from Harris (1996); those for the open clusters NGC 2420 and M 67 are from WEBDA (http://www.univie.ac.at/webda/). The RV ($V_r$) listed for NGC 2420 and M 67 is the average of the literature values (see Section 4.2). The $[\text{Fe}/\text{H}]$ of NGC 2420 and M 67 is based on the high-resolution spectroscopy described by Gratton (2000).

$a$ Reddening from Harris (1996).

$b$ Reddening from Schlegel et al. (1998).

$c$ Apparent diameter of the cluster in arcminutes from Dias et al. (2002).
estimates of RVs and line indices (Stoughton et al. 2002). Tests of the quality of stellar RVs from the SSPP (which uses initial estimates from the SDSS processing pipelines) indicate that precisions better than 5 km s$^{-1}$ are achieved for brighter stars, with zero-point offsets of no more than a few km s$^{-1}$, respectively (Paper III). These errors degrade for fainter stars, as expected.

An initial set of candidate member stars of the globular and open clusters studied in the present paper was selected on the basis of photometric and astrometric data (proper motions) from the literature. The central cores of the clusters were not targeted because the PHOTO pipeline does not resolve the very crowded fields into single-star detections, and also due to limitations on the separations of the fibers during the spectroscopic follow-up stage. The primary method for selecting member candidates was performed by plotting a photometric CMD for a given cluster, and choosing stars from regions of this diagram that correspond to locations on the MS TO or RGB of the cluster. An additional list of bright stars for M 15 and M 2 with previously available proper motions consistent with membership in the clusters was provided by Cudworth (1976), K. M. Cudworth (2006, private communication) and Cudworth & Rauscher (1987). Other stars in the fields of these clusters were used to fill spectroscopic fibers using the default SEGUE target selection algorithm (Adelman-McCarthy et al. 2008). While many of these additional targets turned out to be stars from the general field populations, a significant fraction turned out serendipitously to be members of the clusters.

For M 13, three specially designed plug plates were obtained. Two of the three plug plates followed the standard SEGUE target selection procedure (Adelman-McCarthy et al. 2008) of sampling stars with a variety of spectral types based on the SDSS imaging and PHOTO processing. An additional set of likely M 13 members, including several stars that were saturated in the SDSS imaging ($r < 14.5$) and with coordinates from Cudworth & Monet (1979) and K. M. Cudworth (2006, private communication), was added to the target list for the third plug plate with high priority (bumping ordinary SEGUE targets), in order to obtain spectra of several likely giant-branch and HB members.

In the case of NGC 2420, the stars chosen for spectroscopy were primarily targeted from the SDSS photometry obtained by the PHOTO pipeline, using the normal SEGUE target selection algorithm. Additional stars with apparent magnitudes in the range $14.5 < g < 20.5$ that fell within 0.5 deg from the center of NGC 2420 were also targeted for spectroscopy. However, due to crowding, if two objects were within 55$''$ of one another, then only one received a fiber. Thus, not every star in the central region of NGC 2420 was targeted. There were about 480 objects selected in this way, including a number of noncluster members that are located in the NGC 2420 field.

For M 67, the initial targets came from the SDSS imaging data processed by the PHOTO pipeline. However, for this cluster, many candidate members with positions, magnitudes, and colors from the WEBDA (http://www.univie.ac.at/webda/) catalogs were added to the target lists. The bright targets (with $r < 14$) saturate the SDSS imaging camera, so these were added from the literature (Sanders 1989; Fan et al. 1996). Such bright stars present difficulties for regular SDSS spectroscopic observations (such as scattering light onto adjacent fibers), so they were exposed for shorter than normal integration times. About 200 very bright stars between about $12 < g < 14$ were targeted.

Note that in each cluster field some stars with no pre-existing ugriz photometry from the PHOTO pipeline were also targeted from the catalogs in the literature. For these stars, we obtained ugriz photometry from the DAOPHOT procedure.

In total, we obtained SDSS spectroscopy for 1920, 1280, 1280, 1280, and 640 targets, including sky spectra and calibration object spectra, in the fields of M 13, M 15, M 2, NGC 2420, and M 67, respectively. Therefore, the total number of selected member stars will vary from cluster to cluster. The particular clusters that were chosen were essentially set by their presence (or not) in the SDSS-I/SEGUE footprint, since the usual observing process requires that photometry be available prior to spectroscopic targeting. Some otherwise problematic clusters were included as a result. For example, M 2 presents a special challenge for separation of its likely members from the general field population, as its RV is close to zero, where it strongly overlaps with several Galactic stellar populations. In addition, this cluster is the most distant among the sample under investigation. Thus, the spectra obtained are generally of lower S/N than the rest of our sample. However, M 2 is located in the equatorial stripe ($-1.27 < \delta < 1.27$), which was scanned multiple times during SDSS-I and SDSS-II; hence, we have very accurate photometry to employ. For the remaining sample of clusters with available photometry, we attempted to cover as wide a metallicity range as possible for spectroscopic study. The reduced spectra were processed through the SSPP in order to estimate $T_{\text{eff}}$, $\log g$, and [Fe/H], among other quantities.

Table 1 summarizes the global properties of the clusters under consideration in this paper, taken from the compilation of Harris (1996) for the globular clusters and from the literature, and WEBDA or Gratton (2000), for the open clusters.

### 3. Radial Velocities

There are two estimated RVs provided from the SDSS spectroscopic pipeline. One is an absorption-line redshift obtained by cross-correlating the spectra with templates that were acquired from SDSS commissioning spectra (Stoughton et al. 2002). Another comes from matching the spectra with ELODIE template spectra (Prugniel & Soubiran 2001). In most cases, the velocity based on the ELODIE template matches appears to be the best-available estimate, as spectra of “quality assurance” stars with multiple measurements show the most repeatable values for this estimator. We adopt this velocity in most of our analysis. A more detailed description of the determination of the best-available RV, and of the zero-point offsets in the RVs, can be found in Paper I.

### 3. Membership Selection from the Spectroscopic Samples

Owing to an insufficient number of stars with available spectroscopy for each cluster, it is not possible to obtain a well-defined CMD based solely on spectroscopically observed stars. Thus, we make use of photometric data in the field of each cluster. Below we describe how we obtain relatively clean CMDs for individual clusters, and select likely member stars from the spectroscopic data.

#### 3.1. Likely Member Star Selection for Globular Clusters

One of the primary issues that one needs to address when creating a CMD for a star cluster, or for selecting likely member stars, is the removal of contamination from field stars. In order to approximately isolate the likely cluster members from the
field stars along the line of sight, we have made use of the CMD mask algorithm described by Grillmair et al. (1995). We illustrate the basic idea by the application of this algorithm to the M 13 field shown in Figure 1. We first select all stars inside the estimated tidal radius (25′; Harris 1996), shown as the innermost green circle in Figure 1. This is regarded as the cluster region. The red dots represent stars with available photometry from the SDSS PHOTO pipeline (Lupton et al. 2001); the black dots are stars with photometry obtained from DAOPHOT. The blue open circles indicate stars with available spectroscopy. We then choose an annulus outside the cluster region, indicated in the figure as the region between the two black circles, as the field or background region.

We next obtain CMDs of each region, spanning \(-1.0 \leq (g - r)_0 \leq 1.5\) and \(12 \leq g_0 \leq 22\), and then subdivide these diagrams such that the size of each subgrid is 0.2 mag wide in \(g_0\) and 0.05 mag wide in \((g - r)_0\) color. The total number of subgrids for the CMDs in each region is thus 2500 (50 \times 50).

Figure 3 shows the resulting CMDs of the cluster (left panel) and field (right panel) regions, overplotted with squares representing the selected subgrids, obtained as described below.

We first calculate the signal to noise \((s/n)\) in each preliminary subgrid by the application of Equation (1) over the entire CMD region shown in Figure 3. Here, we assume that the field stars outside the tidal radius are uniformly distributed throughout the annulus area:

\[
s/n(i, j) = \frac{n_c(i, j) - gn_f(i, j)}{\sqrt{n_c(i, j) + g^2n_f(i, j)}}. \tag{1}
\]

In the above, \(n_c\) and \(n_f\) refer to the number of stars in each subgrid with color index \(i\) and magnitude index \(j\), counted within the cluster region and field region, respectively. The parameter \(g\) represents the ratio of the cluster area to the field area.
The following procedures are applied in order to find the optimal range of colors and magnitudes that correspond to the likely members of each cluster. First, we sort the elements of \( s \) in descending order, so that we obtain a one-dimensional array of \( s \) with index \( l \); the array element with the highest \( s \) corresponds to \( l = 1 \). The next step is to obtain star counts in gradually larger regions of the CMDs. The accumulated area is represented as \( a_k = k a_0 \), where \( a_0 = 0.01 \text{ mag}^2 \), which is the same for all subgrids, and is the area of a single subgrid in the CMD array, and the \( k \) is the number of subgrids to combine. Finally, the cumulative signal-to-noise ratio, \( S/N(a_k) \), as a function of \( a_k \), is calculated from

\[
S/N(a_k) = \frac{N_c(a_k) - g N_f(a_k)}{\sqrt{N_c(a_k) + g^2 N_f(a_k)}}
\]

(2)

where

\[
N_c(a_k) = \sum_{l=1}^{k} n_c(l), \quad N_f(a_k) = \sum_{l=1}^{k} n_f(l).
\]

(3)

The parameter \( n_c(l) \) denotes the number of stars within the cluster region having ordered color–magnitude index \( l \); \( n_f(l) \) represents the same quantity for the field region. Based on the maximum value of \( S/N(a_{k_t}) \), a threshold value of \( s/n \) is picked in order to select high-contrast surface-density areas (i.e., high \( s/n \)) between the cluster and field regions. These are considered to be the subgrids that contain likely cluster members. After removing single-star events in areas of the CMDs where the field-star density is low, all stars in subgrids with \( s/n(i, j) \) greater than the threshold value of \( s/n \) are selected. These stars are considered as the photometrically likely member stars for a given cluster.

The red squares shown in the left panel of Figure 3 are the subgrids with \( s/n \) greater than the threshold value; the corresponding subgrids in the field region are shown as green squares in the right panel of this figure. Figure 6 depicts the CMD of the selected likely members of M 13 from the photometry data, shown as black dots. The same procedures are performed to differentiate the likely member stars of M 15 and M 2, based on photometry alone. The top left and right panels in Figure 2 show fields in the vicinity of M 15 and M 2, respectively. Due to the lack of photometry data (the available scans do not allow for full regions, centered on the cluster, to be examined), the field regions (black circles in the figure) are offset from the clusters. Furthermore, the cluster region for M 15 is a bit smaller than the tidal radius for this cluster. Choosing a smaller region for M 15 does not affect our analysis, since the full tidal radius of M 15 is considered as we select likely members from the spectroscopic sample. Figure 4 shows the CMDs of the cluster and field regions for M 15 (top) and M 2 (bottom), with the subgrids determined.

We now proceed to select the stars that are likely members of the globular clusters from the available spectroscopic sample. This step begins by the selection of the stars within the cluster tidal radii that pass the photometric criterion for membership, based on their location on the cluster CMDs according to the algorithm described above.

Figure 6 displays the cleaned CMD of M 13, overplotted with the likely members from the spectroscopic sample (shown as red circles). The same procedures are carried out to identify likely member stars of M 15 and M 2 from their spectroscopic data. The top left and right panels in Figure 7 are the cleaned CMDs of M 15 and M 2, respectively, with the likely members indicated by the red open circles. At this stage of the analysis there are 458 likely members for M 13, 164 for M 15, and 105 for M 2 identified. Additional cuts, based on the derived metallicity
3.2. Likely Member Star Selection for Open Clusters

Since the fields of nearby open clusters are not as crowded as those of globular clusters, the S/N between the cluster region and the background region is not sufficiently high to select likely cluster members by means of the CMD mask algorithm (see the bottom panels of Figure 2). As an alternative, we first obtain a fiducial line for an open cluster (including its MS and subgiant branch, if it exists) by the use of an robust polynomial fitting procedure. As an example, the left panel of Figure 5 displays the CMD of the NGC 2420 field inside a radius of 0.3 deg from the center of the cluster. According to the open cluster catalog of Dias et al. (2002), the apparent diameter of this cluster is only 5° on the sky, but we prefer to adopt a 18′ radius, in order to include as many member stars as possible. The red line is the fiducial line derived from the robust polynomial fit. The blue lines are the upper and lower limits (fiducial ±0.06 mag in \((g - r)_{0}\)) determined by eye. Stars from the spectroscopic sample that fall within the 18′ radius and inside the blue limit lines in Figure 5 are identified.

A similar procedure is applied to M 67, except that a 30′ (an apparent diameter of 25′; Dias et al. 2002) radius and fiducial ±0.10 mag in \((g - r)_{0}\) are used. The bottom panels of Figure 7 depict the selected likely member stars as red circles (from the spectroscopic data) and black dots (from the photometry data). Based on this method, there are 238 stars and 65 (66) selected stars for NGC 2420 and M 67, respectively. The first listed number for M 67 indicates the stars with available estimates of [Fe/H] from the SSPP, while the quantity in parentheses represents the number of stars with available RVs. Additional cuts, based on the derived metallicity estimates and RVs, in order to select “true member stars,” are described in Section 4.4.

4. Determination of Overall Metallicities and Radial Velocities of the Clusters

In order to investigate the accuracy of our derived metallicities and RVs, we now consider the global distribution of these parameters obtained from the current version of the SSPP for the likely cluster members. In this section, we describe a method to isolate “true member stars” from the selected likely member stars from the spectroscopic samples described above. We then use these subsamples to determine our best estimates of the
Figure 5. CMDs of the NGC 2420 (left) and M 67 (right) fields. The red line is the fiducial obtained by the application of a robust fourth-order polynomial fit. The stars inside the blue lines, determined by offsets from the adopted fiducial of ±0.06 (NGC 2420) and ±0.10 (M 67) mag in \((g - r)_0\), are regarded as likely member stars from the photometric sample.

Figure 6. M 13 CMD based on the likely member stars (black dots) selected from the photometric sample. The likely members identified from the spectroscopic sample are indicated with red open circles.

4.1. Selection of True Members

We establish the criteria for carrying out metallicity and RV cuts as follows.

The left panel of Figure 8 illustrates the [Fe/H] distribution for three different subsamples of stars in the region of the globular cluster M 13. The first, shown as the black dot–dashed line, represents the distribution of derived metallicities for the 1714 stars with available estimates of [Fe/H] along the line of sight to this cluster. Note that this distribution includes numerous stars that cannot be considered members of the cluster, as they cover a much wider range of [Fe/H] than might be expected if they were drawn exclusively from the cluster member population. The dot–dashed line in the right panel of Figure 8 shows the RV distribution of these same stars.

The red dashed line in the left panel of Figure 8 is the distribution of [Fe/H] for the 458 likely members selected from the spectroscopic sample as described in Section 3. We obtain a Gaussian fit to the highest peak of the distribution of these stars (red dashed line in Figure 8), and obtain an estimate of the mean \(\langle [\text{Fe}/\text{H}] \rangle\) and standard deviation \((\sigma)\) for this distribution. Similar fits are obtained for the distribution of RVs for the likely members shown in the right panel of Figure 8. On the basis of these fits, we now trim likely outliers by the application of a \(2\sigma\) clipping procedure, for example,

\[
\langle [\text{Fe}/\text{H}] \rangle - 2\sigma_{[\text{Fe}/\text{H}]} \leq [\text{Fe}/\text{H}] \leq \langle [\text{Fe}/\text{H}] \rangle + 2\sigma_{[\text{Fe}/\text{H}]} \quad (4)
\]

\[
\langle \text{RV} \rangle - 2\sigma_{\text{RV}} \leq \text{RV} \leq \langle \text{RV} \rangle + 2\sigma_{\text{RV}}. \quad (5)
\]

In the above, \([\text{Fe}/\text{H}]\), and RV, correspond to the values of these parameters for each star under consideration. The stars surviving both of these clips are considered true cluster members for the purpose of this study. Note that at no point have we considered the external “known” values of [Fe/H] and RV for the clusters as a whole.

The same procedure is performed for stars in M 15, M 2, NGC 2420, and M 67. Based on the application of these membership cuts, we now have a total of 293 stars identified as true members of M 13, 98 stars as true members of M 15, 76 stars as
true members of M 2, 163 stars as true members of NGC 2420, and 52 stars as true members of M 67. The distributions of [Fe/H] and RV for the surviving members (true cluster members) of M 13 are shown as green histograms in the left and right panels of Figure 8, respectively. Similar plots for M 15, M 2, NGC 2420, and M 67 are shown in Figures 9–12, respectively. M 2 is the most distant object among the clusters considered in this study, and the S/N of the spectra obtained for its members is generally lower than for stars in the other clusters of our sample. This results in a smaller number of stars with reliable [Fe/H] estimated than for the other globular clusters.

4.2. Determination of Overall Estimates of Mean Cluster Metallicity and Radial Velocity

We now obtain final estimates of the cluster metallicities and RVs, based on Gaussian fits to the surviving true member stars for each cluster, as shown by the blue curves in Figures 8–12. The parameters in the top half in Table 2 summarize these determinations. The mean and 1σ spread of the metallicities of the true member stars are listed in Columns (2) and (3), respectively; Columns (4) and (5) are for the RVs. Column (6) lists the total number of selected true member stars associated with each cluster, based on our analysis. External estimates of the metallicities and RVs for the globular clusters, adopted from the Harris (1996) compilation, are listed in Columns (7) and (8). The RVs for the open clusters are averages of literature values. See Section 5 for the details. Column (9) lists metallicity estimates for these clusters obtained from high-resolution spectroscopy of a limited number of brighter stars by Kraft & Ivans (2003) for M 15 and M 13, I. I. Ivans (2007, private communication) for M 2, and Gratton (2000) for NGC 2420 and M 67.

We have checked to see if there is any change of the mean and scatter of our derived metallicity and the RV for the clusters.
if we impose only RV cuts (and not metallicity cuts) to the membership selection. As seen in the lower half of Table 2, little change in these quantities occurs. The total number of the true members identified is not much different either. Thus, cluster membership could have been made by consideration of the RV, tidal radius, and CMD alone.

In order to check for trends in our metallicity determinations as a function of color or quality of the spectra, the distribution of [Fe/H] for the true member stars of each cluster, as a function of $(g - r)_0$ (left panel) and $(S/N)$, the average S/N per pixel for spectra of member stars over the 4000–8000 Å region (right panel), is shown in Figure 13. The red line is the literature value listed in Table 2; the green dashed line applies to our derived mean estimates. Although, as expected, the scatter becomes larger with declining $(S/N)$, large trends in the residual estimates of [Fe/H] as a function of color or $(S/N)$ are not evident. Table 3 provides a list of regression results for the residuals (relative to the literature estimates of [Fe/H], $\text{RES}_{\text{Fe/H}} = [\text{Fe/H}]_{\text{cluster}} - [\text{Fe/H}]_{\text{lit}}$), as a function of these two variables. The regressions are simple linear models of the form

$$
\text{RES}_{\text{Fe/H}} = A + B \cdot (g - r)
$$

and

$$
\text{RES}_{\text{Fe/H}} = A + B \cdot (S/N).
$$
Column (1) of Table 3 lists the cluster under consideration, while Column (2) is the number of stars considered in the regression. Column (3) lists the independent variable involved in the regression. Columns (4) and (5) list the estimated zero-point and error in this quantity, while Columns (6) and (7) list the slope term and its error. Column (8) lists the value of $R^2$, which measures the amount of variance that can be accommodated by the regression. Low values of this quantity indicate little dependence on the independent variable. The final column lists whether the correlation can be considered significant (S) or not (N), according to the Pearson correlation coefficient. Inspection of this table indicates that the zero-point offsets are acceptably small (the largest being $+0.234$ for the M 15 regression on $g - r$ and $-0.384$ for the M 67 regression on $S/N$). The slope terms are also small, with the exception of that for the M 15 regression on $g - r$. Although six of the ten regressions appear formally significant, according to the Pearson correlation test, note that most of the regressions have low values of $R^2$, suggesting that only a small amount of the variance is taken up by the correlations. The largest values of $R^2$ are $12\%$ for the M 15 (the lowest metallicity cluster considered) regression on $g - r$, and $26\%$ for the M 67 (the highest metallicity cluster considered) regression on $g - r$. We conclude that, while room remains for improvement at the extrema of the cluster metallicity determinations, the SSPP determinations are generally robust with respect to color and $S/N$. 

Figure 10. Same as Figure 8 but for M 2.

Figure 11. Same as Figure 8 but for NGC 2420.
The distribution of the SSPP-derived estimates of metallicity as a function of estimated log $g$, as shown in Figure 14, also confirms that the $[\text{Fe}/\text{H}]$ estimated by the SSPP is reliable over a wide range of luminosity classes; no large trends are found with respect to the surface gravity estimates.

5. A COMPARISON OF DERIVED $[\text{FE/H}]$ AND RADIAL VELOCITY FOR TRUE CLUSTER MEMBERS WITH PREVIOUS STUDIES

In this section, we present a more detailed comparison of our derived metallicity and RV of each cluster with various values reported in the literature.

5.1. M 13 (NGC 6205)

The three spectroscopic plug-plate observations of this cluster provide the largest number (293) of true members selected among the clusters in this study. Our estimate of the mean abundance, $\langle [\text{Fe}/\text{H}] \rangle = -1.59$, is very close to the Harris (1996) estimate ($[\text{Fe}/\text{H}] = -1.54$). However, the recent study of Kraft & Ivans (2003) reported a revised cluster abundance for this cluster, derived from high-resolution spectroscopy of 28 giants. Their value indicates a metallicity for M 13 (based on Fe II lines) that is a bit lower than that given by Harris, $[\text{Fe}/\text{H}] = -1.60$, but only 0.01 dex different from the value we obtained from the SSPP. An alternative $[\text{Fe}/\text{H}]$ (from Fe I lines) reported by these authors indicates a slightly lower value, $[\text{Fe}/\text{H}] = -
Figure 13. Distribution of [Fe/H] as a function of (g − r)$_0$ (left panels) and average ratio of signal to noise (right panels) for selected true member stars of M 13, M 15, M 2, NGC 2420, and M 67. The overall mean [Fe/H] determined in this paper for each cluster is shown with the green dashed line; the red solid line represents the adopted literature value in each panel. No obvious trends exist as a function of either color or S/N.

−1.63. Sneden et al. (2004) obtained [Fe/H] = −1.62 (from Fe i lines) and [Fe/H] = −1.55 (from Fe ii lines), based on a sample of stars observed with the KECK/HIRES spectrograph (R ∼ 45,000). Cohen & Méndez (2005) reported higher values for the metallicity of this cluster, [Fe/H] = −1.50, based on a high-resolution (R = 35,000) analysis of a sample of 25 stars, extending from the giant branch to near the MS TO. Pritzl et al. (2005) determined [Fe/H] = −1.57 from a compilation of high-resolution data in the literature. Very recently, Kirby et al. (2008) obtained medium-resolution (R ∼ 6000) spectroscopy for 69 giants in this cluster, over the wavelength range 6300–9100 Å. They report an average of [Fe/H] = −1.66, which is slightly lower than our estimate. Considering the range of [Fe/H] obtained from previous studies, it is clear that the SSPP determination of overall [Fe/H] for M 13 is in excellent agreement. Our derived spread in the metallicities of the M 13 true member stars (0.13 dex) is also satisfyingly low, especially considering the wide range of temperatures and gravities for true members that are considered here.

Our estimate of the mean RV, ⟨RV⟩ = −244.8 km s$^{-1}$, with a standard deviation of 8.8 km s$^{-1}$, is in good agreement with that given by Harris (1996; −245.6 km s$^{-1}$). It is important to note that, as mentioned in Paper I, we have already added +7.3 km s$^{-1}$ to all DR-6 (Adelman-McCarthy et al. 2008) stellar RVs, in order to correct a recognized systematic offset.

5.2. M 15 (NGC 7078)

There are a total of 98 stars selected by our procedures as true members of this cluster. Our derived overall abundance of
Figure 14: Distribution of [Fe/H] as a function of estimated log g for the selected true member stars of M 13, M 15, M 2, NGC 2420, and M 67. The overall mean [Fe/H] determined in this paper for each cluster is shown with the green dashed line; the red solid line represents the adopted literature value in each panel. No obvious trends exist as a function of surface gravity.

M 15, ⟨[Fe/H]⟩ = −2.19, is close to the value listed by Harris (1996; [Fe/H] = −2.26). Sneden et al. (1997) reported [Fe/H] = −2.40, based on high-resolution spectra for 18 bright giants, in good agreement with the value of [Fe/H] = −2.37 obtained by Sneden et al. (2000), from observations of giants at the tip of the RGB. Kraft & Ivans (2003) obtained [Fe/H] = −2.42 (from Fe II lines) and [Fe/H] = −2.50 (from Fe I lines) for this cluster, based on high-resolution spectroscopy of nine giants. A value of [Fe/H] = −2.38 was reported by Pritzl et al. (2005) from a compilation of high-quality data in the literature. Otsuki et al. (2006) reported [Fe/H] = −2.29 from an analysis of high-resolution spectra obtained for six giants in this cluster. Most recently, Kirby et al. (2008) calculated [Fe/H] = −2.42 from medium-resolution spectra of 44 giants. Since most of the high-resolution analyses indicate [Fe/H] ∼ −2.40 for M 15, this might indicate that the SSPP overestimates [Fe/H] by about 0.2 dex at low metallicities. A forthcoming study of the cluster M 92 (based on SDSS-II data that have only been recently obtained) will seek to confirm this tendency. The spread in the metallicities of true member stars in M 15 reported by the SSPP is quite low (0.17 dex).

Our estimate of the mean RV, ⟨RV⟩ = −108.2 km s⁻¹, with a standard deviation of 11.7 km s⁻¹, agrees very well with that of Harris (1996; −107.0 km s⁻¹).

5.3. M 2 (NGC 7089)

Only a limited number of true member stars (76) are selected by our procedures for this distant cluster, as the spectra obtained by SDSS for this cluster are generally of lower quality than for other clusters in our study. The faintness of M 2 is also a reason it has not received a great deal of attention by studies at high spectral resolution. Our derived average metallicity, ⟨[Fe/H]⟩ = −1.52, is slightly higher than the Harris (1996) value ([Fe/H] = −1.62), but in very good agreement with the value obtained by I. I. Ivans (2007, private communication), [Fe/H] = −1.56. The estimated spread in our derived metallicities, 0.18 dex, is quite small, but larger than the spreads obtained for M 13 and M 15, as expected due to the inclusion of stars in our analysis with low S/N (∼10/1).

Our estimate of the mean RV, ⟨RV⟩ = −2.1 km s⁻¹ with a standard deviation of 9.8 km s⁻¹, is a bit higher (by about 3.2 km s⁻¹) than that provided by Harris (1996; −5.3 km s⁻¹). Although still small, this is the largest offset in RV among the clusters we consider in this study. However, it should be recalled that the mean metallicity of M 2 is quite close to that expected for members of the field halo population ([Fe/H] ∼ −1.6), and its (near zero) RV is buried in the peak of foreground disk stars, which increases the likelihood that noncluster stars could have crept into our true member sample.
5.4. NGC 2420

There are 163 true member stars selected for this open cluster. The mean metallicity of the selected true member stars reported by the SSPP is [(Fe/H)] = −0.38, which is only slightly higher than the value determined by Gratton (2000) from high-resolution spectroscopy of a single member star [(Fe/H)] = −0.44. Friel & Janes (1993) reported [Fe/H] = −0.42 for nine member stars, based on medium- and low-resolution spectroscopic data. Friel et al. (2002) determined [Fe/H] = −0.38 ± 0.07, based on medium-resolution spectra of 20 member stars. The most recent study, by Anthony-Twarog et al. (2006), indicated [Fe/H] = −0.37 ± 0.05, derived from intermediate-band vbyCaHβ photometry. These values agree excellently with our own metallicity estimate for this cluster.

The derived spread in the metallicities of the true member stars is also very low (0.10 dex).

Concerning the RV for this cluster, Friel et al. (1989) derived 80.0 ± 6 km s⁻¹ from six stars. Friel (1993) reported 84.0 km s⁻¹. Scott et al. (1995) determined 67.0 km s⁻¹ from 19 member stars. Rastorguev et al. (1999) reported a value of 71.1 km s⁻¹. The literature value of RV for NGC 2420, as listed in Table 2, is an average of these four values (+75.5 km s⁻¹). This average is in excellent agreement with our derived estimate of +75.1 km s⁻¹, with a standard deviation of 5.9 km s⁻¹.

5.5. M 67 (NGC 2682)

Only one plug plate (640 spectra) has been obtained for this open cluster. This, and the expected large amount of contamination from disk stars, resulted in a relatively small number (52) of true members being identified by our procedures. The SSPP-derived mean metallicity is [(Fe/H)] = −0.08, with a small spread (0.07 dex). This is lower by 0.1 dex than that of Gratton (2000), [Fe/H] = +0.02, derived from a high-resolution study of a single member star. Shetrone & Sandquist (2000) determined [Fe/H] = −0.05 for ten blue stragglers and TO stars, based on high-resolution (R ~ 30,000) spectroscopy. A value of [Fe/H] = +0.02 ± 0.03 was determined by Yong et al. (2005) from a high-resolution (R ~ 28,000) spectroscopic analysis of three member stars. Randich et al. (2006) analyzed ten member stars of this cluster, based on high-resolution (R ~ 45,000) spectroscopy, and derived [Fe/H] = +0.03 ± 0.01. Friel & Boesgaard (1992) computed [Fe/H] = +0.02 ± 0.12 for three F dwarfs observed at medium spectral resolution. From a medium-resolution spectroscopic study of 25 members, Friel et al. (2002) estimated [Fe/H] = −0.15 ± 0.05. Other catalogs of open clusters (e.g., Twarog et al. 1997; Chen et al. 2003) report a solar metallicity for this cluster. All of these literature values agree (within our observed scatter of 0.1 dex) with our metallicity estimate, which suggests that the metallicity estimated by the current version of the SSPP is reliable for stars with abundances near the solar value. Note that this is a marked improvement with respect to previous versions of the SSPP, which tended to underestimate [Fe/H] for solar-metallicity stars by up to 0.5 dex.

For the RV of M 67, Girard et al. (1989) reported 33.6 ± 0.72 km s⁻¹, based on a re-analysis of the compilation of a large set of member stars with RV measurements (Mathieu et al. 1986). Scott et al. (1995) determined 32 km s⁻¹ from 26 member stars. Values of 32 ± 11 km s⁻¹ from four stars, 33 km s⁻¹, and 33.6 km s⁻¹ were estimated by Friel et al. (1989), Friel & Janes (1993), and Rastorguev et al. (1999), respectively. Yong et al. (2005) obtained a very similar value, of 33.3 km s⁻¹, from three member stars. Taking an average of all these measurements, we obtain 32.9 km s⁻¹, as listed in Table 2. This value agrees with our derived mean RV of +34.9 km s⁻¹ within the standard deviation of our measurements, 4.0 km s⁻¹.

As discussed above, taking into account only the scatter in the metallicities and RVs calculated from the members of each cluster, we are able to derive estimates of the typical external uncertainties for the SSPP estimates of these quantities, σ(Fe/H) ∼ 0.13 dex, and σ(RV) ∼ 8.0 km s⁻¹. The scatter in the RV is also noted to increase with decreasing [Fe/H]. This is the expected behavior, since the metallic lines of a metal-poor star are weaker than those of a metal-rich star of the same effective temperature, making it more difficult to identify strong features to anchor the determination of RV. Upon inspection of Table 2 a similar behavior can be found for [Fe/H], that is, larger errors with declining metallicity.

6. A COMPARISON OF DERIVED T_eff AND log g FOR TRUE CLUSTER MEMBERS WITH COLOR–MAGNITUDE DIAGRAMS

In the previous section, we considered the accuracy with which the SSPP obtains estimates of metallicity and RV. We now consider the accuracy with which the SSPP obtains estimates of effective temperatures, T_eff, and surface gravities, log g. One excellent “global” test of these estimates is to examine the locations of the true member stars on the observed CMD (based on the totality of likely photometric member data) for each cluster. One can also compare these estimates with corresponding theoretical CMDs.

Figures 15–19 show plots of the SSPP-estimated temperatures and gravities for true member stars superimposed on the photometrically cleaned CMDs for each of our clusters. Note that in order to obtain the theoretical temperature scales (shown along the top of the left-hand panels in each figure), we make use of a linear relation between (g − r)_0 color and T_eff by performing a least-squares fit in this plane to the theoretical models of Girardi et al. (2004). We choose the isochrones from this study that have the closest [Fe/H] to the derived metallicity of each cluster, and adopt an age of 13.5 Gyr for the globular clusters, 2.2 Gyr for NGC 2420, and 4.3 Gyr for M 67 (adopting the ages from WEBDA for the open clusters). A similar procedure is applied for transforming the (g − r)_0 magnitude to a theoretical log g scale (shown along the far right axis in the right-hand panels of each figure). Distance moduli from the Harris (1996) compilation for the globular clusters and WEBDA for the open clusters (also listed in Table 1 of this study) are used in order to compute apparent magnitudes.

In these figures, we plot the SSPP-estimated parameters for true member stars in different colors, corresponding to different ranges of temperature and surface gravity (as shown in the legend for each plot). Each color represents a range of 500 K in T_eff and 0.5 dex in log g, respectively. The effective temperature estimated by the SSPP appears in excellent agreement for most of the true member stars, with only a few exceptions. Such stars could either be outright errors in the SSPP predictions, or could just be foreground/background stars that survived the various membership cuts we have applied. Inspection of the Figures also reveals the presence of a few stars close to the MS TO in M 13, M 15, and M 2 that appear to have slightly higher or lower SSPP-estimated log g than expected from the theoretical scale. The surface gravities of stars along the RGB appear to be very well estimated. Such behavior is perhaps to be expected, since the stars close to the TO region are at the
Figure 15. Distributions of effective temperature (left panel) and surface gravity (right panel) of the selected true member stars of M 13, based on the spectroscopic sample, superposed on the CMD of likely member stars, based on the photometric sample. Each color represents a temperature range of width 500 K and a surface gravity range of 0.5 dex, respectively. The temperature scales on the top of the left-hand panel come from a linear relation between \((g - r)_0\) color and \(T_{\text{eff}}\) obtained by performing a least-squares fit to the theoretical models of Girardi et al. (2004). A similar procedure is applied for transforming the \(g_0\) magnitude to a theoretical \(\log g\) scale shown on the ordinate on the right-hand panel.

Figure 16. Same as Figure 15 but for M 15. The black dots are the likely member stars based on the photometric sample.
Figure 17. Same as Figure 15 but for M 2. The black dots are the likely member stars based on the photometric sample.

Figure 18. Same as Figure 15 but for NGC 2420. The black dots are the likely member stars based on the photometric sample.
low end of the S/N range that we accept for SSPP parameter determinations (~10/1), and thus are subject to greater errors in the determination of their atmospheric parameters. The RGB stars are among the brightest stars in the globular clusters, and hence are likely to have the best-determined estimates.

A careful inspection of Figure 18 for NGC 2420 indicates that gravity estimates for most of the MS stars are well estimated from the SSPP, with the exception of the faintest stars. These stars have only low S/N (~10/1) spectra available, resulting in higher uncertainties in determinations of their surface gravities. It should also be recalled that surface gravity is a difficult parameter to estimate, especially from spectra of the resolving power obtained by the SDSS. Overall, we are pleased to see as good a behavior in the estimates of this parameter as that demonstrated in Figures 15–19.

In addition, using the derived relations between \((g - r)\) and \(T_{\text{eff}}\), and \(g_0\) and \(\log g\) from the isochrones, we predicted \(T_{\text{eff}}\) and \(\log g\) from the observed \((g - r)_0\) and \(g_0\), respectively. Table 4 lists the averages and standard deviations of the residuals of the effective temperatures and surface gravities between the SSPP estimates and the calculated values. Even though we have employed a simple relationship between \((g - r)_0\) with \(T_{\text{eff}}\), we see good agreement between the SSPP estimates and the theoretical values in \(T_{\text{eff}}\). Although, as expected, there is a rather large offset and scatter in the gravity, indicating a more complex function is needed (or the isochrones themselves are in doubt), the scatters are still within the bin sizes (0.5 dex) for this parameter used in Figures 15–19. The relatively larger zero-point offsets in \(T_{\text{eff}}\) for M 13 and NGC 2420 is caused by the linear relation having to cover a large range of \((g - r)_0\): ~0.4 to 0.8 for M 13 and 0.1–1.2 for NGC 2420. Table 5 lists the observed and derived quantities for all of the individual stars considered as true member stars in the analysis of each cluster. The columns are as defined in the table notes.

### Table 4

| Cluster | \(N\) | \(\langle \Delta \rangle\) | \(\sigma\) | \(\langle \Delta \rangle\) | \(\sigma\) |
|---------|------|-----------------|-------|-----------------|-------|
| M13     | 293  | +165            | 194   | −0.29           | 0.40  |
| M15     | 98   | −13             | 134   | −0.25           | 0.31  |
| M2      | 76   | +31             | 114   | −0.22           | 0.35  |
| NGC2420 | 163  | +71             | 193   | −0.14           | 0.46  |
| M67     | 52   | −31             | 58    | +0.15           | 0.07  |

**Notes.** These values are 5σ-clipped averages and standard deviations. \(N\) is the total number of the selected member stars.

7. SUMMARY

Based on photometric and spectroscopic data reported in SDSS-I and SDSS-II/SEGUE, we have examined estimates of stellar atmospheric parameters and heliocentric RVs obtained by the SSPP for selected true members of three Galactic globular clusters, M 13, M 15, and M 2, and two open clusters, NGC 2420 and M 67, and compared them with those obtained by external estimates for each cluster as a whole.

From the derived scatters in the metallicities and RVs obtained for the selected true members of each cluster, we quantify the typical external uncertainties of the SSPP-determined values, \(\sigma([\text{Fe/H}]) = 0.13\) dex and \(\sigma(\text{RV}) \sim 8.0\) km s\(^{-1}\), respectively. These uncertainties apply for stars in the range of \(-0.3 \leq [\text{Fe/H}] \leq 0.3\) and \(-15 \leq v_t \leq 15\) km s\(^{-1}\), respectively.
Table 5
Properties of Selected Member Stars of M 13, M 15, M 2, NGC 2420, and M 67

| spSpec name | R.A. (deg) | Decl. (deg) | RV (km s$^{-1}$) | $\sigma_{RV}$ (km s$^{-1}$) | $T_{eff}$ (K) | $\sigma_{T_{eff}}$ (K) | $\log g$ (dex) | $\sigma_{\log g}$ (dex) | [Fe/H] (dex) | $\sigma_{[Fe/H]}$ (dex) | $u$ | $\sigma_{u}$ | $g$ | $\sigma_{g}$ | $r$ | $\sigma_{r}$ | $i$ | $\sigma_{i}$ | $z$ | $\sigma_{z}$ | $\langle S/N \rangle$ |
|-------------|------------|-------------|------------------|-----------------------------|--------------|-------------------------|--------------|-------------------------|-------------|--------------------------|---|----------|---|----------|---|----------|---|----------|---|----------|------------------|
| M 13        |            |             |                  |                             |              |                         |              |                         |             |                          |   |          |   |          |   |          |   |          |   |          |                      |
| 53521–2174–054 | 250.8113861 | 36.380367   | −238.4           | 5.2                         | 5617         | 28                      | 2.80         | 0.22                    | −1.67       | 0.04                     | 19.000 | 0.029 | 17.834 | 0.014 | 17.388 | 0.020 | 17.231 | 0.020 | 17.166 | 0.020 | 21.2 |
| 53521–2174–082 | 250.6566925 | 36.292824   | −241.1           | 1.8                         | 5183         | 23                      | 2.18         | 0.21                    | −1.55       | 0.03                     | 16.884 | 0.017 | 15.434 | 0.013 | 14.854 | 0.020 | 14.634 | 0.019 | 14.501 | 0.017 | 55.0 |
| 53521–2174–087 | 250.5986176 | 36.141987   | −231.8           | 3.5                         | 5544         | 5                       | 2.95         | 0.16                    | −1.51       | 0.04                     | 18.419 | 0.022 | 17.259 | 0.016 | 16.794 | 0.018 | 16.623 | 0.019 | 16.539 | 0.021 | 29.3 |
| 53521–2174–093 | 250.6486664 | 36.331833   | −242.5           | 1.9                         | 5088         | 34                      | 2.04         | 0.18                    | −1.71       | 0.04                     | 16.775 | 0.009 | 15.301 | 0.012 | 14.644 | 0.036 | 14.384 | 0.020 | 14.238 | 0.032 | 57.3 |
| 53521–2174–094 | 250.6187286 | 36.193378   | −234.7           | 3.6                         | 5514         | 36                      | 2.96         | 0.19                    | −1.51       | 0.05                     | 18.417 | 0.022 | 17.252 | 0.016 | 16.780 | 0.018 | 16.555 | 0.019 | 16.468 | 0.021 | 30.3 |
| 53521–2174–098 | 250.6272430 | 36.530879   | −250.5           | 1.6                         | 5127         | 22                      | 2.11         | 0.18                    | −1.80       | 0.03                     | 16.991 | 0.009 | 15.598 | 0.009 | 14.992 | 0.029 | 14.735 | 0.020 | 14.601 | 0.032 | 54.8 |
| 53521–2174–121 | 250.5334473 | 36.323925   | −249.2           | 1.9                         | 5326         | 20                      | 2.46         | 0.15                    | −1.52       | 0.01                     | 17.558 | 0.015 | 16.225 | 0.010 | 15.698 | 0.013 | 15.486 | 0.014 | 15.393 | 0.016 | 48.1 |
| 53521–2174–126 | 250.4946899 | 36.287205   | −232.9           | 3.9                         | 5400         | 64                      | 2.83         | 0.12                    | −1.62       | 0.02                     | 18.250 | 0.021 | 17.014 | 0.013 | 16.536 | 0.012 | 16.337 | 0.014 | 16.276 | 0.015 | 33.2 |
| 53521–2174–128 | 250.4741516 | 36.309807   | −252.8           | 4.0                         | 5421         | 76                      | 3.23         | 0.16                    | −1.64       | 0.04                     | 18.654 | 0.020 | 17.480 | 0.008 | 17.022 | 0.013 | 16.825 | 0.014 | 16.752 | 0.016 | 24.8 |
| 53521–2174–131 | 250.4893646 | 36.332115   | −242.8           | 2.0                         | 5113         | 39                      | 2.09         | 0.14                    | −1.65       | 0.07                     | 16.692 | 0.013 | 15.203 | 0.007 | 14.582 | 0.007 | 14.840 | 0.000 | 14.163 | 0.008 | 58.3 |

Notes. The column labeled spSpec name is constructed from the Modified Julian Date (five digits), the spectroscopic plug-plate number (four digits), and the fiber used (three digits). The error in the listed RV is computed from ELODIE template matching. The atmospheric parameter estimates ($T_{eff}$, $\log g$, and [Fe/H]) are the adopted values from the SSPP (Paper I); the quoted internal error is the listed uncertainty in each value. The photometric errors in each band are based on the PHOTO pipeline (Lupton et al. 2001). In the last column, $\langle S/N \rangle$ is the average signal to noise per pixel of the spectra, calculated over the range 3850–6000 Å.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)
$g - r \leq 1.3$ and $2.0 \leq \log g \leq 5.0$, at least over the metallicity interval spanned by the clusters studied ($-2.3 \leq [\text{Fe}/\text{H}] \leq 0.0$). Therefore, the metallicities and RVs obtained by the SSPP appear sufficiently accurate to be used for studies of the kinematics and chemistry of the metal-poor and near-solar-metallicity stellar populations in the Galaxy. We have also confirmed that $T_{\text{eff}}$ and log $g$ are sufficiently well determined by the SSPP to distinguish between different luminosity classes, through a comparison with theoretical predictions.

In a forthcoming paper, we will compare the predictions of the SSPP with intermediate-metallicity clusters ([Fe/H] = $-0.7$) and with additional near-solar-metallicity populations, as sampled by metal-rich globular clusters and nearby open clusters. Additional metal-poor clusters will also be examined.

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