

# The Metallicity Distribution Functions of SEGUE G and K dwarfs: Constraints for Disk Chemical Evolution and Formation

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## ABSTRACT

Using the G and K dwarfs from the Sloan Extension for Galactic Understanding and Exploration (SEGUE) survey, we determine the metallicity distributions of cool stars in the Milky Way disk system. This portion of the Sloan Digital Sky Survey (SDSS) contains spectra for approximately 41,500 G and 23,800 K dwarfs, a significantly larger sample, both numerically and spatially, than previous spectroscopic analyses. Comparison of these two spectral types, and their variation in metallicity with respect to Galactic position, provides important guidance for models of the formation and chemical evolution of the Milky Way's thick-disk component. SEGUE has a well-defined, quantitative target-selection algorithm, based on *ugriz* photometry and proper motions; this

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allows us to adjust our spectroscopic sample such that it accurately represents the underlying Milky Way populations. Combining atmospheric parameters, determined by an optimized version of the SEGUE Stellar Parameter Pipeline, with various isochrones, we calculate the distance to each star, accurate to  $\sim 12\%$ . We then quantify the variation in metallicity with respect to spatial position from the Galactic center ( $R$ ) and the plane of the Galaxy ( $|Z|$ ). Our unbiased observations of G and K dwarfs provide valuable constraints for chemical and dynamical Galaxy evolution models, with particular utility for thin- and thick-disk formation theory. Although our uncertainties in the radial metallicity gradient are large, we are consistent with the results from Cheng et al., estimating a negative gradient below  $|Z|$  of 1 kpc that flattens above this height. Both spectral types also exhibit a consistent decrease in  $[\text{Fe}/\text{H}]$  with increasing  $|Z|$ , approximately  $-0.3$  dex/kpc. Comparison with the sample of Lee et al., which distinguishes between the thin and thick disk using  $[\alpha/\text{Fe}]$ , suggests that this gradient reflects the transition in G and K dwarfs from a thin-disk dominated sample at small  $|Z|$  to a sample consisting primarily of thick-disk stars above  $|Z|$  of 1 kpc. We compare our distributions to those of two different models of the Galaxy: the population synthesis model TRILEGAL (Girardi et al. 2004) and that of Schönrich & Binney which simulates chemical and dynamical evolution. Both models show little change in  $[\text{Fe}/\text{H}]$  with respect to  $|Z|$  and are unable to replicate the metallicity distributions we observe above  $|Z|$  of 0.5 kpc. This result is not surprising, as the existing chemical constraints on Galaxy models are limited to the solar neighborhood, which is thin-disk dominated.

*Subject headings:* astronomical databases: miscellaneous – astronomical databases: surveys – Galaxy: abundances – Galaxy: disk – Galaxy: evolution – Galaxy: formation – Galaxy: stellar content – Galaxy: structure – stars: abundances – stars: distances

## 1. Introduction

A lingering puzzle in astrophysics is how the Milky Way formed and evolved, both chemically and dynamically. In particular, the development of the dual-component disk is poorly constrained. Gilmore & Reid (1983) first detected the thick disk in the Milky Way when they determined that the stellar number density as a function of  $|Z|$  was best fit by two components<sup>1</sup>, one with a scale height of approximately 300 pc, and the second with a scale height of 1350 pc. Analyses by Gilmore & Wyse (1985); Wyse & Gilmore (1995), and Chiba & Beers (2000) established that the two populations

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<sup>1</sup>The likely existence of a second stellar component close to the Galactic plane was previously noted by Yoshii (1982), who referred to it as a halo component, even though its inferred density was 10 times that of the local halo. The Yoshii (1982) normalization relative to the local thin disk (0.01–0.02) and scale height ( $\sim 2$  kpc) were commensurate with the values later determined by Gilmore & Reid (1983) (0.02, and 1.5 kpc, respectively). See also Yoshii et al. (1987).

were distinct in  $[\text{Fe}/\text{H}]$ . The so-called thick disk was metal poor, with a peak metallicity around  $[\text{Fe}/\text{H}] = -0.6$ , in contrast to the thin disk, with a peak metallicity typically around  $[\text{Fe}/\text{H}] = -0.2$ . Further observation, such as that of Soubiran et al. (2003), revealed that the two populations were also kinematically distinct. Finally, chemical analyses, separating the populations kinematically, determined that the two populations differed with respect to the  $\alpha$ -elements as well (Fuhrmann 1998; Prochaska et al. 2000; Bensby et al. 2003, 2005; Reddy et al. 2006). Thick-disk stars have enhanced  $\alpha$ -element abundances with respect to iron,  $[\alpha/\text{Fe}]$ , whereas  $[\alpha/\text{Fe}]$  ratios are lower in thin-disk stars. This measurement is consistent with observations that thick-disk stars are generally older than thin-disk stars, with ages of around 8 Gyr and up (Fuhrmann 1998). Thus, analyses of the disk components via solar neighborhood targets indicates the two are distinct with respect to chemistry, kinematics, and age.

Similar disk structure has been observed in numerous galaxies (Burstein 1979; Dalcanton & Bernstein 2002; Yoachim & Dalcanton 2008a,b), including those at redshifts as high as  $z \sim 3$  (Elmegreen & Elmegreen 2006). We can use the Milky Way to disentangle the mechanisms behind this regularly occurring feature. There is a wide range of formation and evolution models that claim to recreate the disk structure. Until recently, we lacked an adequate observational sample to quantitatively test these models and examine the structure of the disk system. Analyses of the chemical abundances of late-type stars, such as G and K dwarfs, are particularly useful for examining the formation and development of the Milky Way disk, because they have lifetimes comparable to the age of the Galaxy. The abundances of these stars, young and old, reflect the chemical development of the Galaxy; they are a fossil record of chemical evolution.

Initial examination of the chemistry of local G dwarfs revealed the “G-dwarf problem” (van den Bergh 1962; Wyse & Gilmore 1995; Rocha-Pinto & Maciel 1996; Favata et al. 1997). Early models of star formation and chemical evolution, such as the simple closed box model of Schmidt (1963), predicted many more low-metallicity G dwarfs than were actually observed. It was suspected that the G-dwarf problem arose from observational biases, namely that metal-rich stars are brighter and thus likely to be over-represented in a magnitude-limited sample. However, the deficiency of low-metallicity stars persisted in later observational samples which corrected for these biases. Work such as the Geneva-Copenhagen survey of the solar neighborhood (Jørgensen 2000; Nordström et al. 2004; Holmberg et al. 2007, 2009; Casagrande et al. 2011) indicates that for a large volume-complete and kinematically-unbiased sample, the simple closed box model overpredicts the number of cool metal-poor dwarfs even more than was originally reported.

Discovery of the G-dwarf problem prompted analyses of the metallicity distribution of cooler stars. Work such as Mould (1982), Favata et al. (1997), Flynn & Morell (1997), Rocha-Pinto & Maciel (1998), and Kotoneva et al. (2002) suggested that the dearth of metal-poor stars continued down the spectral sequence to both K and M dwarfs. Unfortunately, these analyses are hampered by small sample size; the low luminosity of these spectral types makes constructing a complete sample beyond the solar neighborhood difficult. It is still unclear whether the metallicity distribution of K and M dwarfs are consistent with that of G dwarfs.

Models of chemical evolution have advanced far beyond the simple closed box model to examine the G- (and K-) dwarf problem. Current models experiment with the initial mass function (Chiappini et al. 2000; Romano et al. 2005), inflows of low-metallicity material (Larson 1972; Chiappini et al. 2001), or commencing star formation from already metal-enhanced material (Truran & Cameron 1971). These Galactic chemical evolution models, such as the two-infall model of Chiappini et al. (1997), use the G-dwarf metallicity distribution function (MDF) as a valuable test of their accuracy. Unfortunately, this comparison is typically limited to the solar neighborhood, which is thin-disk dominated. An MDF that covers a larger volume of space, and reaches to lower temperatures, will allow modelers to look beyond our immediate surroundings and study the chemical evolution of the disk as a whole.

In addition to examining chemical evolution models, the metallicity structure of G and K dwarfs allow a comparison of Galaxy formation models, specifically, those that try to recreate the formation and dynamical evolution of the thin and thick disk. There are two primary scenarios for thick-disk formation: secular evolution and merger scenarios. Secular evolution models include disk heating via spiral density waves (Fuchs 2001; Minchev & Quillen 2006), a central bar (Martin & Roy 1994; Friedli et al. 1994), and radial migration (Sellwood & Binney 2002; Roškar et al. 2008; Schönrich & Binney 2009a,b; Loebman et al. 2010; Minchev & Famaey 2010; Minchev et al. 2011). Radial migration involves stars moving radially from the inner to the outer regions of the disk, and vice versa, due to scattering by transient spiral structure (Sellwood & Binney 2002) or diffusion caused by overlap of bar-spiral resonances (Minchev & Famaey 2010; Minchev et al. 2011; Brunetti et al. 2011). As stars move outward, they experience a lower gravitational restoring force from the less-dense outer disk, allowing them to move more in the vertical direction, resulting in a “puffed-up” disk. It has been proposed that migration alone can be responsible for the thick disk (Schönrich & Binney 2009a; Loebman et al. 2010). However, a possible problem for thick-disk formation via radial migration was pointed out by Minchev et al. (2011), where these authors demonstrated that stellar samples migrating radially outwards *decrease* their vertical velocity dispersion by as much as 50% as a result of adiabatic cooling.

Building off of the secular evolution models, Katzantidis et al. (2008) suggest that vertical heating to create a thick disk can originate in a minor merger. Similarly, a minor merger or close encounter with a satellite can encourage radial-migration processes (Quillen et al. 2009; Bird et al. 2011). This scenario naturally enhances the expected amount of radial mixing, making it easier for this mechanism to form the thick disk. The thick disk can also result from early accretion of gas-rich material (Brook et al. 2004, 2005), although it is unclear that this material must originate in a merger scenario (Bournaud et al. 2009). Finally, Abadi et al. (2003) propose that the thick disk can be formed purely of stars from merging satellites.

Of particular importance for distinguishing between disk formation models is the variation in metallicity with respect to radial and vertical distance. For example, the Larson (1976) model of inside-out disk growth predicts a negative radial metallicity gradient; this work proposes that inner portions of the disk will collapse rapidly, forming stars and chemically enriching their surroundings

before the outer parts of the disk. This version of the simple slow-collapse model will also create a vertical metallicity gradient for the same reasons (Larson 1976). In contrast, disk formation via stellar accretion, as presented by Abadi et al. (2003), will result in no metallicity gradient with respect to distance from the plane, as the final  $|Z|$  value of the stars does not depend on their  $[\text{Fe}/\text{H}]$ .

The effect of radial migration on the radial and vertical metallicity gradient varies significantly depending on assumed parameters, such as the star formation history. Older stars have more time to move out in both the radial and vertical directions. If one assumes older stars are consistently more metal poor, this effect results in a vertical metallicity gradient via the age-dispersion relation (e.g., Aumer & Binney 2009). As the stars are being regularly mixed in the radial direction, this will likely reduce any pre-existing radial metallicity gradient. However, these predictions are highly dependent on various assumptions for overall chemical evolution and the age-metallicity relationship, which studies such as Edvardsson et al. (1993) have shown to remain unclear (see also the discussion by Loebman et al. (2010)).

Past work has examined the MDF with respect to  $R$  (e.g., Allende Prieto et al. 2006; Ivezić et al. 2008; Cheng et al. 2011; Lee et al. 2011b) and  $|Z|$  (e.g., Allende Prieto et al. 2008; Ivezić et al. 2008; Breddels et al. 2010; Katz et al. 2011; Lee et al. 2011b). One difficulty with these analyses has been the lack of a uniform sample of cool stars over a large area with accurate metallicity measurements. Previous large surveys, such as the Geneva-Copenhagen survey that analyzed  $\sim 14,000$  F and G dwarfs in the solar neighborhood, have a large number of targets over a significant area on the sky but rely on Strömgren photometry to determine stellar metallicity (Nordström et al. 2004). Similarly, work with Sloan Digital Sky Survey (SDSS) photometry (York et al. 2000), such as that by Ivezić et al. (2008) and Jurić et al. (2008), utilized a large sample size of stellar targets but determined metallicities from empirical photometric indicators. Photometric calibrations are susceptible to errors from uncertain reddening corrections, have reduced sensitivity for low-metallicity target, and depend strongly on the adopted calibration to spectroscopic determinations. Using spectroscopic measurements increases the accuracy and precision of metallicity determinations, in addition to providing kinematic information such as radial velocities, albeit with the significant added cost of increased observing time.

The low luminosity of cool stars limits the size and scope of existing spectroscopic surveys. Many of these samples are able to probe only a few lines of sight (Arnadottir et al. 2009; Katz et al. 2011) and are therefore limited by small sample size and sky coverage. In particular, it is difficult to obtain spectroscopic data for stars far from the solar neighborhood, which is heavily dominated by thin-disk stars. In contrast, the Sloan Extension for Galactic Understanding and Exploration (SEGUE) survey balances the need for large sample size and sky area with the importance of spectroscopic observation (Yanny et al. 2009). Combining spectroscopy with SDSS *ugriz* photometry over a range of  $14 < g < 20.3$  in  $\sim 3500$  square degrees on the sky, SEGUE provides an ideal sample to examine the chemical abundance distribution in the Galaxy, while avoiding the difficulties associated with purely photometric surveys and issues of small sample size for prior spectroscopic

analyses.

SEGUE has a quantified target-selection algorithm, using a series of photometric and proper motion criteria to isolate different spectral types from the SDSS stellar photometry. The SEGUE G- and K-dwarf sample is based on a  $(g - r)$  color cut and a range of magnitudes in  $r$ . These criteria in conjunction with the results from the SEGUE Stellar Parameter Pipeline (SSPP) results in a sample of 41,540 G and 23,828 K dwarfs with atmospheric parameters over a large volume of the Milky Way disk. Our thorough understanding of the SEGUE spectroscopic target selection allows us to account for any potential sample biases that occur and relate the spectroscopic sample to the photometric sample of cool stars, increasing the scope of our sample from  $\sim 65,000$  to around 650,000 stars.

Thanks to its systematic targeting and coverage over a large portion of the sky, the SEGUE survey provides a well-defined, wide-ranging, uniform sample of G and K dwarfs. Combining our stars with calculated distances, we examine the metallicity distribution with respect to position within the Galaxy. We also compare our calculated distributions to two existing Galaxy models, namely the stellar population synthesis model TRILEGAL (Girardi et al. 2005) and the radial migration model of Schönrich & Binney (2009a,b). These two vary in assumptions and technique; comparison of the SEGUE data and the model predictions explores how well existing models are predicting disk chemistry and structure.

Section 2 explains how we extract our G- and K-dwarf sample from the SEGUE database. Section 3 describes our methodology to account for sample biases using the SEGUE target-selection algorithms. This technique allows construction of a spectroscopic sample that truly represents the Milky Way disk. Section 4 presents our various methods for calculating the distances to each of our targets. In Section 5, we combine our weighting algorithms with our distances to determine the MDF of the two spectral types with respect to  $R$  and  $|Z|$ , comparing them to Galaxy models.

## 2. Sample Selection

The SEGUE survey combines the extensive uniform data set of photometry from SDSS with medium-resolution ( $R \sim 1800$ ) spectroscopy over a broad spectral range (3800-9200Å) for  $\sim 240,000$  stars over a range of spectral types (Yanny et al. 2009). Technical information about the Sloan Digital Sky Survey is published on the survey design (York et al. 2000; Eisenstein et al. 2011), telescope and camera (Gunn et al. 2006, 1998), astrometric (Pier et al. 2003) and photometric (Ivezić et al. 2004) accuracy, photometric system (Fukugita et al. 1996) and calibration (Hogg et al. 2001; Smith et al. 2002; Tucker et al. 2006; Padmanabhan et al. 2008). Beyond its large size, this sample has a homogeneous data set, substantial area coverage, and spectroscopically-determined stellar atmospheric parameters. This work utilizes photometry from Data Release 7 (DR7, Abazajian et al. 2009). The atmospheric parameters are a modified version of those released as part of DR8 (Aihara et al. 2011).

SEGUE selects targets from SDSS for spectroscopic observation based on photometric and proper motion cuts. The resulting spectra are processed through the SSPP, an automated system that determines atmospheric parameters, such as effective temperature, surface gravity, and metallicity (Lee et al. 2008a). Details of this system and its calibration are available in Lee et al. (2008a,b), Allende Prieto et al. (2008), Smolinski et al. (2011), and Lee et al. (2011a). The SSPP employs 6 primary methods for the estimation of  $T_{\text{eff}}$ , 10 for the estimation of  $\log g$ , and 12 for the estimation of  $[\text{Fe}/\text{H}]$ . For an in-depth description of SSPP calculations and processes, see Lee et al. (2008a,b). This program’s outputs have been checked against high-resolution spectra of stars within globular and open clusters, as well as in the field (Lee et al. 2008b; Allende Prieto et al. 2008; Smolinski et al. 2011). The uncertainties of the SSPP for targets with  $S/N=25$  per pixel, where each pixel is  $\approx 1\text{\AA}$ , are  $\sigma(T_{\text{eff}})=200$  K,  $\sigma(\log g)=0.4$  dex, and  $\sigma([\text{Fe}/\text{H}])=0.3$  dex (Lee et al. 2008a). These uncertainties increase as the  $S/N$  decreases: for  $S/N=10$ ,  $\sigma(T_{\text{eff}})=260$  K,  $\sigma(\log g)=0.6$  dex, and  $\sigma([\text{Fe}/\text{H}])=0.45$  dex (Lee et al. 2008a).

The SEGUE “G dwarfs” are defined as having  $14.0 < r_0 < 20.2$  and  $0.48 < (g-r)_0 < 0.55$ , while the “K dwarfs” have  $14.5 < r_0 < 19.0$  with  $0.55 < (g-r)_0 < 0.75$  (Yanny et al. 2009), where the subscript 0 indicates dereddening and absorption correction using Schlegel et al. (1998) values. For K dwarfs, these constraints correspond to a temperature range of  $\approx 4800\text{--}5300$  K for  $[\text{Fe}/\text{H}]$  from  $-0.5$  to  $-2.5$ . Over this metallicity range, G dwarfs have a temperature range of  $\approx 5000\text{--}5600$  K. In this paper, we will refer to the SEGUE “G and K dwarf” categories simply as G and K dwarfs. Extracting every star from SEGUE spectroscopy which matches these color and magnitude criteria results in 50,210 G and 26,834 K dwarfs. We then restrict our sample to targets with  $S/N \geq 10$ , because these spectra have better-constrained and better-understood uncertainties than those with lower  $S/N$  (Lee et al. 2008a). We also eliminate targets where, for various reasons, the SSPP was unable to determine the temperature, metallicity, and/or surface gravity. In addition to catastrophic failures, we remove targets that the SSPP flags due to temperature or noise issues. For example, if the temperature determined for a star by the SSPP and that from a  $(g-z)$  relationship differ by more than 500 K, we eliminate it from our sample. Similarly, if a spectrum is flagged as noisy by the SSPP, we remove it from the sample, even if its reported  $S/N$  is greater than 10. Finally, we select all stars with  $\log g \geq 4.1$  to isolate dwarf stars. This surface gravity cut is discussed further in § 2.1 and 2.3. With these parameter criteria, in conjunction with the color and magnitude limits, we have around 33,300 G and 19,600 K dwarfs. The distribution of our G- and K-dwarf spectroscopic sample in various atmospheric parameters is shown in Figure 1. The values shown for each target are slightly different than those included in DR8 (Aihara et al. 2011); specifically, the  $[\text{Fe}/\text{H}]$  and surface gravity SSPP determinations have been optimized for the sample, as discussed in § 2.1 and 2.2. In turn, modifications in these parameters affects the calculated effective temperature.

## 2.1. Surface Gravity Determinations

The SSPP uses ten methods to estimate surface gravities for stars, each appropriate for a different range in  $(g - r)_0$  (Lee et al. 2008a). Although all of the techniques cover the range of  $(g - r)_0$  appropriate for our sample, they are not all similarly accurate. As shown in Fig. 2, the CaI2 and MgH indicators are systematically low, skewing the adopted surface gravity to lower values. Additionally, the WBG indicator rarely works for the G- and K-dwarf sample; it was designed for evolved stars. Fig. 2 also shows abrupt jumps on the high end of the gravity distributions and an artificial accumulation of stars right below this limit in the K24, KI13, and ANNRR algorithms, but these artifacts are inconsequential to our analysis.

Using the CaI2, MgH, and WBG to determine  $\log g$  will shift the calculated values lower, potentially eliminating some dwarfs from our sample by making their surface gravities indicative of evolved stars. For our targets, we use  $\log g$  values which do not take these three methods into account. This tightens the distribution of surface gravities, diminishing the population that artificially lies in the low-valued tail (see Fig. 2).

## 2.2. [Fe/H] Determinations

As with the surface-gravity estimates, not all of the metallicity-estimation techniques available in the SSPP are accurate for G and K dwarfs. For example, the CaIIK2 and WBG distributions are erratic and spiky (Figure 3). Other techniques, such as CaIIK3, ACF, ANNSR, and CaIIT, are limited in the metallicity range they cover, only reaching as high as solar metallicity. This limit will bias their measurements towards lower metallicities. We exclude these six techniques from our [Fe/H] determinations.

Finally, there are other methods in the SSPP that appear to have well-behaved distributions in [Fe/H] but are inappropriate for our sample. Two of the Kurucz-model-based methods (KI13, K24) are designed for stars with temperatures greater than 5000 K; there are numerous K dwarfs for which this method is not accurate. The ANNRR method is also problematic; this neural-network technique is based on outdated parameters determined by the SSPP for DR7 (Abazajian et al. 2009). Thus, our [Fe/H] estimates are based solely on NGS2, NGS1, and CaIIK1.

Although these three remaining methods cover the appropriate range of parameter space, they still require adjustment. In particular, all three show artificial peaks. These methods utilize a  $\chi^2$  minimization technique in  $T_{\text{eff}}$ ,  $\log g$ , and [Fe/H] to match target spectra with various synthetic grids. These grids cover a fairly narrow range of parameter space, resulting in the sharply peaked structure. By modifying the  $\chi^2$  interpolation method in parameter space from the [Fe/H] values reported in DR8 (Aihara et al. 2011), these peaks are smoothed, providing a more realistic distribution in [Fe/H].

This revised SSPP was tested on open and globular clusters (see Table 1). The modified



techniques result in negligible shifts to the overall metallicity determined by the SSPP for each cluster, well within the uncertainties. The optimized G- and K-dwarf parameters will be available in the next SDSS public release, DR9, in 2012.

### 2.3. Sample Contamination

In addition to considering uncertainties in the SSPP, we must also examine potential contaminants in the sample that can perturb the parameter determinations, namely undetected binarity and evolved stars. Schlesinger et al. (2010) showed that, for G and K dwarfs, undetected companions have little statistical effect on the distributions of stellar atmospheric parameters determined by the SSPP. For a  $S/N$  of 25, approximately 10% of G-K dwarf stars will have their effective temperature and/or metallicity shifted beyond the SSPP uncertainties by an undetected companion. Binarity also has little effect on the colors of the G- and K-dwarf targets, such that the SEGUE target selection is unaffected. Thus, the effect of binarity is well within the expected errors in SEGUE. However, undetected binarity does contribute uncertainty in our calculated distances; this issue is discussed in § A.2.1.

The second source of sample contamination is from evolved stars. In particular, subgiants can drastically affect our distance calculations, which assumes all of the targets are on the main sequence. SEGUE also targets K giants, which fall into our  $(g-r)_0$  color cut. To isolate dwarf stars we apply a cut on the SSPP  $\log g$ , limiting it to 4.1 and above. However, the uncertainty of the SSPP for  $S/N$  of 25 in surface gravity is  $\pm 0.4$  dex, which allows for possible subgiant contamination.

We use a three-fold approach to examine the extent of the subgiant contamination. First, we use Galaxy models to estimate the number of subgiants expected to fall in our SEGUE G- and K-dwarf sample. Second, we manufacture a series of synthetic spectra at various evolutionary stages and process them through the SSPP, as a test of parameter accuracy. These same techniques can be applied to the sample to examine how many dwarfs may be lost with a stringent cut in  $\log g$ . Finally, we use the Mg index to distinguish between giants and dwarfs in our sample (Morrison et al. 2003).

For each line of sight in the SEGUE sample, we model the distribution of stars using TRILEGAL 1.4 (§ 3.4.1, Girardi et al. 2005). As these are modeled distributions, there are no measurement uncertainties in the stellar parameters. We examine every target with  $(g-r)$  in the G/K dwarf range and  $\log g < 4.2$  to determine the size of possible contamination. The surface-gravity limit for these models is slightly higher than that applied to our sample, as these models are based on Padova isochrones (Girardi et al. 2004), which have the main-sequence turnoff at  $\log g \approx 4.2$ . Combining the proportion of subgiants in the TRILEGAL line of sight with the uncertainty in the SSPP surface gravity measurements, we find that, over all lines of sight, the mean percentage of subgiants that will be identified as dwarfs is approximately  $2 \pm 1\%$ .

We then combine our population analysis with a study of the SSPP surface-gravity deter-

mination using synthetic spectra. We adopt atmospheric parameters from the Dartmouth Stellar Evolution isochrones (Dotter et al. 2008) over a range of metallicity (see § 4.1 for more details about the isochrones). Breaking the isochrones down into 0.01 magnitude blocks in color, we manufacture synthetic spectra for both giants and dwarfs using MARCS model atmospheres processed through TurboSpectrum (Gustafsson et al. 2008; Alvarez & Plez 1998). Our MARCS model atmospheres assume solar scaled abundances, with the solar composition from Grevesse et al. (2007), and plane parallel geometry. They cover a range in effective temperature from 4700-5800 K,  $-2.5$  to  $+0.5$  in  $[\text{Fe}/\text{H}]$ , and 1.2 to 5 in  $\log g$ . Each of these spectra was adjusted to a range of  $S/N$ : 50, 25, and 10. We also analyzed the non-degraded spectra. The spectral synthesis and noise-modeling processes are discussed in more detail in Schlesinger et al. (2010).

Each of these simulated spectra is then processed through the SSPP. As noted earlier, we ignore the  $\log g$  calculations made using the CaI2, MgH, and WBG methods. A comparison of the calculated parameters and those input in the models for  $S/N \sim 25$ , the most common  $S/N$  for the G- and K-dwarf sample, is shown in Figure 4. At a  $S/N$  of 25, the surface gravity tends to be underestimated by 6%, less than the listed SSPP uncertainties. No giants or subgiants will be identified as dwarfs by their  $\log g$  values. As  $S/N$  decreases, the uncertainties in the SSPP parameters increase. At the lowest signal to noise ratio in our sample, there is a 2% chance of a subgiant being identified as a dwarf by the SSPP. From our population studies of the galaxy models, we expect approximately 2% of stars that fall into our G- and K-dwarf color cuts to be subgiants and  $\sim 2\%$  of these will be misidentified as dwarfs by the SSPP, resulting in a less than 1% chance that a subgiant will be counted as a dwarf in our sample.

Our final check on the extent of evolved-star contamination uses the Mg index (Morrison et al. 2003). At a given  $[\text{Fe}/\text{H}]$ , giants will have a smaller Mg index value (i.e., less atomic Mg and MgH absorption) than dwarfs. Binning in metallicity, we use proper-motion criteria to isolate the control sample of “true” dwarf stars. We then examine the spectra of targets where the Mg index is lower than expected for the true dwarfs, i.e., they are in the parameter space of evolved stars. Approximately 1–5% of these outliers were evolved stars, less than 1% of the total sample, confirming that we expect little subgiant and giant contamination in our sample.

The SSPP’s tendency to underestimate surface gravity prevents subgiant contamination. However, it also means that a number of dwarf stars will fall out of the sample when it is selected using a surface-gravity cut. In particular, we will preferentially lose high-metallicity stars, as these have surface gravities closer to the boundary of  $\log g$ .

This proclivity to lose dwarfs, and the rare possibility of gaining a subgiant, can affect our MDF. To quantify this effect, we run a Monte Carlo analysis on modeled lines of sight from the TRILEGAL Galaxy models (§ 3.4.1). For the modeled sample, we select G- and K-dwarf “spectroscopic” targets, based on SEGUE photometric criteria. We examine the variation in the sample with respect to  $[\text{Fe}/\text{H}]$ , comparing the true distribution to that when we convolve the  $\log g$  error of  $\pm 0.6$  dex, the largest possible SSPP uncertainty, with a Gaussian. After multiple iterations, we compare the

different distributions in  $[\text{Fe}/\text{H}]$  to the original, with the modeled surface gravities. The metallicity distribution changes a negligible amount, indicating that surface gravity uncertainties have little effect on our estimates of metallicity structure.

### 3. Accounting for Observational Biases

For our G- and K-dwarf sample to accurately reflect the parameters and distributions of these spectral types in the Galactic disk, we must ensure that we remove any observational biases in our sample. SEGUE uses a systematic quantified target-selection algorithm to identify stars for spectroscopic observation. This consistent algorithm allows us to adjust our spectroscopic sample such that it reflects the properties of the underlying stellar populations. Each SEGUE plug-plate<sup>2</sup> covers a circular region of 7 square degrees, probing the sky with 640 spectroscopic fibers. The G- and K-dwarf stars assigned spectroscopic fibers are randomly selected from the photometric stars that meet the target-selection criteria.

There are four main biases in the spectroscopic sample. First, the G- and K-dwarf sample criteria overlap with other SEGUE categories, e.g., the metal-poor and K-giant targets. Oftentimes these overlapping categories isolate particular regions of parameter space, in particular metallicity, which will result in a bias in the G- and K-dwarf sample. The second bias arises from our limited number of fibers, since we cannot spectroscopically observe every target in a field. To examine the Milky Way distributions, we must adjust our sample such that it reflects the underlying population of stars in apparent-magnitude space. Third, the G- and K-dwarf criteria consist of a simple color and magnitude cut. This cut in  $(g - r)_0$  isolates a different range of masses at each metallicity, resulting in a bias as lower-mass stars are more abundant than higher-mass stars in a given volume. Finally, some of the most metal-rich G dwarfs may have evolved off of the main sequence, making this portion of our sample deficient. We must investigate the effect of age and evolution on the metal-rich end of the distribution.

#### 3.1. Target Selection

For an individual SEGUE line of sight, approximately 375 and 95 fibers are allotted to G and K dwarfs, respectively. Some of the earliest SEGUE plates have different target-selection algorithms than later plates, because target-selection criteria and the number of fibers devoted to each type evolved slightly over time. For G and K dwarfs, we limit ourselves to pointings which fall under the SEGUE, rather than SEGUE2, program, as SEGUE2 does not explicitly target G and K dwarfs. Additionally, we eliminate any pointings that do not have both bright and faint plates; this requirement ensures we probe the same magnitude range for all lines of sight. Finally,

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<sup>2</sup>Throughout the rest of this work, we will refer to plug-plates simply as plates.

we eliminate pointings that have significant Galactic extinction in the  $r$ -band. We determine the extinction per plate by calculating the average  $r$ -band extinction in the DR7.PhotoObjAll table for every object listed as a star. This extinction is derived from the measurements in Schlegel et al. (1998). As SEGUE plates are largely directed away from the plane of the Galaxy, all but 11 of the plates (1888, 2052, 2179, 2300, 2334, 2335, 2623, 2669, 2679, 2680, and 2805) have extinction less than 0.5 mags in  $r$ .

To correct for the effects of target selection, we compare the spectroscopic sample from a particular plate to the underlying population, utilizing SDSS photometry. Each line of sight has a different distribution of spectral types. In addition, the total number of stars in each line of sight varies (e.g., there are fewer stars at high Galactic latitudes). Thus, we must correct for the target-selection biases on a plate-by-plate basis. For each bright and faint plate combination, we extract every possible photometric stellar target within the plate radius. We then match each of these stars with photometry from the DR7.PhotoObjAll database. We then select every photometric target that fulfills the color and magnitude requirements of G and K dwarfs. Finally, we match the photometry and spectroscopy for each plate. For each line of sight, this produces a record of every stellar object within the plate region, and whether or not it was observed spectroscopically.

Matching photometry and spectroscopy is not a trivial task because some plates were observed multiple times, and many stars were repeated, some unintentionally as geometric overlaps from multiple plates and others as purposeful re-observations. Additionally, targets from SEGUE were occasionally observed again as part of SEGUE2. All SEGUE spectroscopic observations have a sciencePrimary parameter, which identifies the best observation, which we use in our spectroscopic selection to isolate the observation with the highest  $S/N$ . We also trim our spectroscopic sample to eliminate any poor observations, removing all targets that have  $S/N < 10$ , an incalculable  $[\text{Fe}/\text{H}]$ , or specific warning flags. These targets remain within the photometric sample.

### 3.1.1. *Distribution of Target Types*

As their selection criteria are based purely on color and magnitude, G and K dwarfs are identified by some of the simpler criteria in SEGUE. However, a number of other samples, such as low-metallicity stars, overlap with the G- and K-dwarf sample. SEGUE categories often focus on specific ranges in parameter space, stars with low metallicity or small proper motions. As these targets fulfill multiple target-type criteria, they have multiple opportunities to be assigned a spectroscopic fiber. This leads to an overabundance of these other stellar categories in the G- and K-dwarf sample. To account for this effect, we compare the distribution of target types in the photometric sample to that of the spectroscopic sample. Alternatively, one could extract only stars assigned fibers as G and K dwarfs. However, this greatly diminishes the size, and thus, the utility, of the sample.

Every stellar target observed photometrically by SDSS is labeled with the SEGUE categories

it fulfills; any individual star can be labeled with multiple target types, i.e., a K-dwarf and a low-metallicity target. We compare the various target identifications between the photometric and spectroscopic sample for each individual line of sight, assigning a weight for each target type, such that the proportion in the spectroscopic sample reflects that of the underlying photometric sample. This action removes biases due to the overlapping target types in SEGUE, be they over- or under-sampled by the spectroscopic fibers. This correction typically increases the proportion of metal-rich stars for both spectral types; K dwarfs are more affected by this adjustment, as they are allotted fewer fibers overall and thus tend to be more contaminated than G dwarfs by other stellar categories. K dwarfs have a mean target-type weight of 1.7 versus 0.7 for G-dwarfs.

### 3.1.2. Calculating $r$ -Magnitude Weights

Once we have ensured that the spectroscopic sample reflects the larger photometric information in spectral type, we weight each spectroscopic target by magnitude. This allows our spectroscopic sample to reflect the number of G and K dwarfs along each line of sight, which is particularly important with respect to latitude. As lower latitude pointings are closer to the plane of the Galaxy, they have many more stars; these stars tend to be more metal rich than those at high latitudes, which sample more of the metal-poor thick disk. Thus, the  $r$ -magnitude weights tend to increase the proportion of metal-rich stars.

To calculate these  $r$ -magnitude weights, we separate the spectroscopic and photometric sample into G and K dwarfs based on  $(g-r)_0$  color. With the G and K sample, we examine the distribution in  $r_0$  magnitude for each individual spectral type, binning up the spectroscopic and photometric targets in 0.5 magnitude bins from  $r_0 = 13$  to 21.5 magnitudes. We compare the number of spectroscopic targets in each bin to the number of potential targets in the photometric sample. The inverse of this ratio is the weight assigned to each spectroscopic target with a measurable  $[\text{Fe}/\text{H}]$  and  $S/N \geq 10$  to recreate the parent photometric distribution. This quantity, which we refer to as the  $r$ -magnitude weight, accounts for the fact that SEGUE does not have unlimited fibers. There are more K than G dwarfs in the underlying photometric distribution. Thus, the  $r$ -magnitude weights are higher, with a mean of around 13.9, whereas the  $r$ -magnitude weight for G dwarfs is around 10.

### 3.1.3. Completeness - Magnitude Limits

Examining the distributions of  $r_0$  magnitude for the photometric and spectroscopic samples reveals that, for the G dwarfs, there are very few usable spectroscopic targets at the faintest magnitudes. This sample extends to  $r_0$  of 20.2, where it is difficult to achieve the necessary  $S/N$ . However, there are often many photometric targets at these faint magnitudes. As there are only a few valid spectroscopic G-dwarf targets representing many stars from the photometric sample,

these stars have very large  $r$ -magnitude weights. The magnitude criteria for K dwarfs in SEGUE are significantly more conservative than that of the G dwarfs; thus, the K-dwarf sample does not have the same faint-end completeness problem.

To determine the true magnitude range of the usable spectroscopic sample, we examine the cumulative distribution of spectroscopic targets in  $r_0$  for each plate. We find that 85% of all spectroscopic G dwarfs have  $r_0 \leq 18.45$ . By setting 18.45 as our faint magnitude limit for G dwarfs, we avoid anomalous weighting. We also must examine the completeness at the bright end for both samples. Due to saturation issues, the SDSS photometry is not complete brighter than 15<sup>th</sup> magnitude in  $r_0$ . Thus, we limit our magnitude range for both G and K dwarfs to  $r_0 \geq 15$ .

### 3.2. Mass-Function Weighting

The  $(g - r)_0$  cut that defines the G- and K-dwarf targets samples a different range of masses at each metallicity. The stars with  $0.48 \leq (g - r)_0 < 0.55$  at  $[\text{Fe}/\text{H}]$  of  $-0.5$  are more massive than those at  $[\text{Fe}/\text{H}]$  of  $-2.0$ . Mass functions for the Galaxy predict a larger number of less massive stars, biasing the SEGUE sample toward more metal-poor stars. The masses probed by our color and metallicity range are typically from 0.5 to  $1.0 M_\odot$ . As this is a fairly small mass range, the corrections for mass function are not large, much less than those for target-type and  $r$ -magnitude weighting. Despite being a minimal effect, we must adjust our spectroscopic sample such that each metallicity bin is scaled to sample the same portion of the mass function. Similar to the other two adjustments, the mass-function weights increase the proportion of metal-rich stars.

We employ the TRILEGAL 1.4 models (§3.4.1), which utilizes a Chabrier mass function, to estimate this effect. For every line of sight, we extract all targets that fulfill the G- or K-dwarf color and magnitude criteria and have surface gravities associated with the main sequence. We then bin up the sample for each spectral type by metallicity. For each bin, we compare the number of stars that fulfill the G- or K-dwarf criteria to the number of targets in the appropriate magnitude and surface-gravity range with masses between 0.5 and  $0.6 M_\odot$ . This ratio indicates how much to scale each metallicity bin of G or K dwarfs to simulate sampling the same region of the mass function. As the mass function varies slightly from plate to plate, we calculate these weights for each SEGUE pointing. The mean mass-function weight for G and K dwarfs is comparable, around 0.9.

We also calculate mass weights based on the Schönrich & Binney (2009a,b) Galaxy models (SB) as a test (§3.4.2). The distribution of weights from the SB models is comparable to the mass-function weights derived from the TRILEGAL simulation; using SB values rather than TRILEGAL has a negligible effect on the metallicity distribution. The TRILEGAL models cover a wider metallicity range than those of Schönrich & Binney (2009a,b), reaching lower metallicities, so we use these weights throughout our analysis.

### 3.3. Evolutionary Effects

Finally, we must determine the effects of stellar evolution on the sample. Figure 5 shows two sets of isochrones with ages of 10 Gyr, the Yale Rotating Evolution Code (YREC, An et al. 2009) and the Dartmouth Stellar Evolution models (Dotter et al. 2008), for a range of metallicities in  $(g - r)$  vs  $M_r$  space. The G- and K-dwarf SEGUE color-cut regions are indicated. These two isochrone sets vary slightly from each other in metallicity range and  $\alpha$ -enhancement; more information about the two is provided in § 4.1 and § 4.2. Note that the Dartmouth isochrones only extend to the main-sequence turn off; the YREC set extend slightly beyond this point to include portions of the subgiant branch.

For both the YREC and Dartmouth isochrones, the most metal-rich isochrones have the main-sequence turnoff before reaching the red edge of the color range for the SEGUE G dwarfs. This is a more severe issue for the Dartmouth isochrones than for the YREC isochrones; at  $[\text{Fe}/\text{H}]=0$ , the main-sequence turnoff for the Dartmouth isochrones lies in the middle of the G-dwarf color band, whereas the YREC isochrone at this metallicity covers the entire range. The Dartmouth isochrones also exhibit similar problems for the K dwarfs, whereas the YREC isochrones indicate that the most metal-rich K dwarfs should generally fall in the SEGUE specified range.

The metal-rich YREC isochrones are normalized to match metal-rich open clusters, namely NGC 2862 and NGC 6791 (An et al. 2009). Judging by this calibration, our G-dwarf sample should not have significant evolutionary bias. To investigate the extent of this evolutionary effect on G dwarfs, we compare the metal-rich samples of the two spectral types. If evolution off the main sequence causes significant biases, the metal-rich G-dwarf fraction should be substantially less than that of the K dwarfs. Over a volume-complete distance range for both G and K dwarfs, approximately 19% of G dwarfs have metallicities greater than 0. Around 15% of K dwarfs are this metal rich. As we see a comparable fraction of G and K dwarfs at the metal-rich end, we do not expect that stellar evolution has a significant effect on the SEGUE G-dwarf sample.

### 3.4. Testing the Target-Selection Weighting on Galaxy models

To ensure that our weighting algorithm appropriately removes biases from target selection, we test it on a series of modeled lines of sight from the theoretical galaxy models of TRILEGAL 1.4 (Girardi et al. 2005) and SB (Schönrich & Binney 2009a,b). With these samples, we know the distribution of stars with respect to metallicity and other stellar parameters.

#### 3.4.1. The TRILEGAL Galaxy Models

The TRILEGAL 1.4 program (Girardi et al. 2005) allows us to simulate different lines of sight and assume a range of Galaxy parameters. Rather than traditional Galaxy modeling, which

relies on an empirical luminosity function, TRILEGAL utilizes a derived luminosity function, built from an assumed star-formation rate, age-metallicity relation, and initial mass function. These parameters vary slightly for different components of the Galaxy. We specify an exponential thin disk with a two-step star-formation rate. The thin disk is assigned a scale length of 2800 pc and a scale height which increases with stellar age, as described in Girardi et al. (2005). The assumed age-metallicity relationship for this component is based on the empirical determination from Rocha-Pinto et al. (2000), and includes  $\alpha$ -enhancement at lower  $[\text{Fe}/\text{H}]$ . The thick disk is also modeled as an exponential, with a scale height of 800 pc and a scale length of 2800 pc. In contrast to the thin disk, a constant star-formation rate and a  $Z$  of 0.008 and  $\sigma[\text{M}/\text{H}]$  of 0.1 dex is assumed for the thick disk. This behavior is combined with the Padova evolutionary tracks to produce a derived luminosity function. This model shows good agreement between the observed and predicted star counts when compared to various stellar catalogs, such as 2MASS and Hipparcos. As we show in § 5.5.2, this model is not consistent with the metallicity structure over the Milky Way disk beyond the solar neighborhood. However, as a test of our methodologies and uncertainties it provides valuable guidance.

We manufacture a TRILEGAL model for each SEGUE line of sight, specifying a limiting magnitude of 23.0 in  $r$ , no dust extinction, and no binary contamination over a circular 7 square degree area of the sky. In addition to the thin and thick disk, we specify an oblate spheroid halo and no central bulge.

### 3.4.2. *The Schönrich & Binney Galaxy Models*

The models of Schönrich & Binney (SB, 2009a,b) rely on assumed star formation laws, nucleosynthetic yields, and a Salpeter initial mass function (Salpeter 1955). These models base their star-formation rate on the Kennicutt law (Kennicutt et al. 1998); in contrast to TRILEGAL, Schönrich & Binney (2009a,b) model the expected nucleosynthetic yields in conjunction with inflows, resulting in a predicted age-metallicity relationship, rather than building off an empirical version. In addition, these models include dynamical behavior, specifically, radial mixing, which alters the modeled chemical structure. Schönrich & Binney (2009b) compare the modeled vertical density structure to that of Jurić et al. (2008) and Ivezić et al. (2008), finding that the model accurately predicts the density structure of various Galaxy components.

The SB model of the Galaxy is built using the BASTI isochrones (Pietrinferni et al. 2004), artificially widened to represent the photometric errors of SDSS. Thus, the expected uncertainties derived from applying our techniques on these models should accurately reflect those of the SEGUE sample. This model has been tested on the Geneva-Copenhagen survey (Nordström et al. 2004; Haywood 2008) and with updated parameters from Casagrande et al. (2011). Schönrich & Binney (2009a) have shown that their model accurately reflects the properties of stars in the solar neighborhood.



### 3.4.3. *Weighting Effectiveness*

We treat each TRILEGAL and SB line of sight as a photometric sample for SEGUE target selection, labeling all modeled stars which meet the color and magnitude criteria of the SEGUE G- and K-dwarf categories. We randomly select 375 G and 95 K dwarfs for each line of sight as our “spectroscopic” observations, weighting this mock SEGUE sample according to the methodology discussed in §3.1.2 and §3.2. We then compare the weighted parameter distribution in  $[\text{Fe}/\text{H}]$  in two ways to that of the underlying sample. First, we compare the “spectroscopic” sample, weighted in target type and  $r$ -magnitude, to the modeled photometric sample (see Fig. 6). The combination of these two weights recreates the metallicity distribution for all modeled stars that fulfill the G- and K-dwarf criteria. This suggests that our photometry-based weighting techniques allow us to examine the metallicity structure of the underlying stellar populations in the disk using our spectroscopic sample.

Our second comparison, shown in Fig. 7, uses the target-type,  $r$ -magnitude, and mass-function weight to recreate the distribution of all stars that meet the G- and K-dwarf magnitude criteria and fall in a uniform mass range. The underlying photometric sample we tested the target-type and  $r$ -magnitude weights on is slightly biased in mass, as explained in §3.2. The top plot compares a  $(g - r)$  color cut to a mass cut in metallicity space. There is little difference between the two distributions. The bottom plot indicates that the color cut manifests as a bias towards metal-poor stars. Our target selection weights account for this, removing the color cut effect such that it appears our sample is extracted from a uniform portion of the mass function. We also tested this on the SB galaxy models with similar results.

## 4. Distance Determinations

Distances are critical both for determining a volume-complete MDF and for examining the behavior of these stars over the different regions of the Galaxy. As these stars lack trigonometric parallaxes, we must estimate distances for each target. We used two different sets of isochrones to determine the distances to our G- and K-dwarf targets: Dartmouth (Dotter et al. 2008) and the empirically corrected YREC isochrones (An et al. 2009, Fig. 5). We test both the different isochrone sets on SDSS data of various open and globular clusters. These two sets cover slightly different metallicity ranges, with Dartmouth ranging from  $[\text{Fe}/\text{H}]$  of  $-2.5$  to  $+0.5$  and YREC from  $-3.0$  to  $+0.4$ . Additionally, the metallicity range is sampled differently and there are variations in the values for  $[\alpha/\text{Fe}]$  between the two grids.

#### 4.1. Dartmouth Isochrones

We match each target to a Dartmouth isochrone based on its SSPP-determined  $[\text{Fe}/\text{H}]$  value. For each star, we use cubic interpolation, via the routine provided by the Dartmouth group, to calculate a new isochrone, matching the star in  $[\text{Fe}/\text{H}]$ . We assume an isochrone age of 10 Gyr (the uncertainties associated with this value are discussed in § A.2.2). We also limit our comparison to the main sequence, as we expect all of our targets to be in this evolutionary stage. Interpolating in color, we match each target to its isochrone in  $(g - r)_0$ , until the color matches within 0.001 mag. We then extract the isochrone parameters, such as effective temperature and the absolute magnitude in  $ugriz$ , for the  $(g - r)_0$  color match. Using the distance modulus, we derive a distance in each filter and adopt the mean distance over all filters as our final value.

#### 4.2. YREC Isochrones

We follow a similar methodology as described in § 4.1 to extract stellar parameters for each target from the YREC isochrones. However, rather than using cubic interpolation to calculate an entirely new isochrone matching each target’s metallicity, we linearly interpolate at a constant  $(g - r)$  between isochrones for this set, assuming an age of 10 Gyr and that all of our targets lie on the main-sequence portion of the isochrones. Using the stellar metallicity, we then extract the absolute  $ugriz$  magnitudes for each target from the isochrones and calculate the mean distance over all of the SDSS filters.

We tested our interpolation method two ways. First, we compared results using linear interpolation to those from cubic interpolation, finding little difference between the stellar parameters determined from these two schemes. We also tested the interpolation method with Dartmouth isochrones, comparing the results from manufacturing a new isochrone to those from interpolating between bracketing isochrones, finding little difference. Thus, we are confident that using linear rather than cubic interpolation has a negligible effect on calculated distances.

#### 4.3. Distance Uncertainties

We compare the distances calculated from the two sets of isochrones in Fig. 8. The distances from the Dartmouth isochrones tend to be larger than those from the YREC isochrones, as they typically return brighter absolute magnitudes for the same  $[\text{Fe}/\text{H}]$ ,  $(g - r)$ , and age (see Fig. 5); the mean difference between the two methods is around 5%. Finally, we calculate distances using two other sets of isochrones and examine the random and systematic uncertainties in these distance calculations in Appendix A. Using propagation of errors, in addition to testing on Galaxy models that replicate the SEGUE photometric and stellar parameter uncertainties, we expect our distance errors to be around 12%. We also calculate distances using the photometric parallax relationship

from Ivezić et al. (2008, their eqn. A7) and compare with our determinations. More information about this analysis is available in Appendix C.

#### 4.4. Testing our Calculated Distances on Globular and Open Clusters

Few of our targets have measured parallaxes; thus, we cannot directly confirm that our calculated distances are appropriate. We instead test our methods against actual SDSS spectra of stars in open and globular clusters, observed for testing the SSPP determinations and SDSS photometry (Lee et al. 2008b; An et al. 2009; Smolinski et al. 2011). Unfortunately, many of these studies focused on stars past the main-sequence turnoff, because they are considerably brighter than dwarfs. We have targets along the main sequence for the clusters M13, M67, NGC 2420, and NGC 6791. This limits us to a metallicity range from  $[\text{Fe}/\text{H}]$  of  $-1.54$  to  $+0.30$ .

We select stars with well-determined  $[\text{Fe}/\text{H}]$ ,  $S/N \geq 10$ , and  $\log g \geq 4.1$  to ensure that our cluster members are on the main sequence. We do not cut on  $(g-r)_0$  color for the globular clusters because this action would severely limit our sample size. Furthermore, our distance calculations should hold for any star on the main sequence. As a check, we determined the average distance to the cluster derived from a color-constrained sample to that from the larger main-sequence sample; they match within the expected errors in distance. Thus, a color cut would not significantly affect our distance measurements to these clusters.

The calculated cluster distances are listed in Table 2, in addition to other parameters from Harris (1996), Lee et al. (2008b), Smolinski et al. (2011), and the WEBDA database. A comparison of the clusters and YREC isochrones is shown in Figure 9. The observed stars agree well with the shifted YREC isochrones. The published distances to these clusters vary considerably (Harris 1996; Kraft & Ivans 2003; An et al. 2009; Smolinski et al. 2011); thus, we are pleased with the general agreement we observe from our isochrone methods. The YREC system has been specifically designed to work with SEGUE, and reaches a more metal-poor value than the Dartmouth isochrones, so we adopt an isochrone matching technique based on the YREC set for our G- and K-dwarf distance calculations.

#### 4.5. Volume Completeness: Distance Range for Different Spectral Types

Using the YREC isochrone technique, we calculate distances ranging from 0.39 to around 6.0 kpc for K dwarfs and 0.5 to 6.0 kpc for G dwarfs (see Fig. 8). To define a volume-complete sample, we use the modified magnitude limits of  $r_0$  from 15 to 18.45 for G dwarfs and 15 to 19 for K dwarfs (§ 3.1.3).

We examine the YREC isochrones for a metallicity of  $[\text{Fe}/\text{H}]$  of  $+0.4$  and  $-3.0$ , extracting the  $r$ -band magnitudes for targets with  $(g-r)$  of 0.48, 0.55, and 0.75. Using the distance modulus, we

calculate the maximum and minimum distance for both spectral types over a range of metallicity. For K dwarfs, the distance range for SEGUE volume completeness is from 1.19 to 1.84 kpc; for G dwarfs, the distance range is from 1.59 kpc to 2.29 kpc. In this paper, we refer to the distance range from 1.59 to 1.84 kpc as the volume-complete distance range. These distance limits are used in comparisons between the G- and K-dwarf sample. For analysis of an individual spectral type, we use the larger distance range associated with either G or K dwarfs. We refer to this range as the spectral type distance.

## 5. Metallicity Distribution Functions for SEGUE G and K Dwarfs

With our optimized G- and K-dwarf sample, we use the target-type,  $r$ -magnitude, and mass-function weights to determine the metallicity distribution functions in G and K dwarfs for the Galaxy. Figure 10 shows the original and adjusted MDF for G and K dwarfs over all the SEGUE lines of sight for the spectral type distance range.

As explained in § 3.1.1, 3.1.2, and 3.2, the corrections for SEGUE target selection biases significantly affect the MDF, increasing the metal-rich end. Applying them to our sample allows us to use our distance-limited sample of approximately 7,830 G and 5,400 K dwarfs to reflect the properties of  $\sim 52,600$  G and 91,500 K dwarfs.

### 5.1. Calculating Uncertainties for the Metallicity Distributions

We use a two-pronged approach to estimate the uncertainties in our MDF. First, we run a bootstrap analysis on our data set. We create multiple versions of the sample by randomly selecting G and K dwarfs and examine the variation in the metallicity distributions of these iterations, comparing with our actual result. This method folds in uncertainties in distance, atmospheric parameters, photometry, and target-selection weights, while also taking into account that we do not know the true underlying metallicity distribution. The derived uncertainties are listed in Table 3 for both G and K dwarfs over different distance ranges; the uncertainty in each bin varies over the distribution but is on average around  $\pm 30\%$  for both G and K dwarfs.

The bootstrap analysis does not take into account correlated uncertainties; specifically, the effect of the error in  $[\text{Fe}/\text{H}]$  on distances. Overestimating the metallicity will lead to an overestimate in distance, and vice versa. As we limit our sample in distance, metallicity errors will force some stars in and others out of the sample. Most importantly, uncertainties in  $[\text{Fe}/\text{H}]$  will broaden the true metallicity distribution. To estimate the size of these effects, we perform a Monte-Carlo analysis on the TRILEGAL modeled lines of sight. For each modeled G- and K-dwarf star, we vary the  $[\text{Fe}/\text{H}]$ , convolving the SSPP errors with a Gaussian, and adjust the corresponding distance to account for this change in metallicity. We then compare the different Monte Carlo iterations to the true distribution (see Fig. 11). The cumulative distributions of G and K dwarfs indicate

that the  $[\text{Fe}/\text{H}]$  and distance error broadens the MDF of the TRILEGAL model. To quantify the extent of this effect, we estimate the slope of the cumulative distribution between fractions 0.25 and 0.75. Larger uncertainties in  $[\text{Fe}/\text{H}]$  will manifest in larger negative slopes in this portion of the cumulative distribution. We have listed the broadened slopes in Figure 11.

## 5.2. Variations with Respect to Spectral Type

Benefiting from the homogeneous SEGUE sample, we can directly compare our G- and K-dwarf MDF. Past work by Favata et al. (1997) found a distribution of nearby K-dwarf stars that was significantly more deficient in metal-poor stars than their G-dwarf sample. They conjectured that this result could originate from either a metallicity bias in their original catalog or metal-enhanced cool star formation. However, later work by Rocha-Pinto & Maciel (1998) found their K-dwarf sample in good agreement with their G dwarfs. Similarly, Kotoneva et al. (2002) found a much broader distribution of K dwarfs with respect to  $[\text{Fe}/\text{H}]$  than Favata et al. (1997). Likely, the narrow distribution of K dwarfs in Favata et al. (1997) was due to small sample size and a tendency to target brighter stars for spectroscopy.

We compare the distribution of the weighted SEGUE G and K dwarfs over a volume-complete range in Figure 12. Our analysis confirms the work of Rocha-Pinto & Maciel (1998), which found the distribution of metallicity in G and K dwarfs in the solar neighborhood to be in good agreement. For our volume-complete region for the G and K dwarfs, i.e., between 1.59 and 1.84 kpc, both spectral types peak at around  $[\text{Fe}/\text{H}]$  of  $-0.5$ , consistent with the peak metallicity for the  $\alpha$ -enhanced sample identified by Lee et al. (2011b). The peak agreement of the two spectral types implies that the chemical enrichment and star-formation history for the two classes are quite similar.

We note that, although they peak at the same  $[\text{Fe}/\text{H}]$ , the K-dwarf distribution appears to be slightly more metal poor overall than that of the G dwarfs. The median weighted metallicities differ by around 0.04 dex. Additionally, the K dwarfs have a more prominent metal-poor tail. The shift in  $[\text{Fe}/\text{H}]$  may be due to contamination of the K-dwarf sample by metal-poor K giants. However, our Mg index analysis found that less than 1% of our sample are likely evolved stars, making it unlikely that this offset is caused by giants (§ 2.3).

Alternatively, this metallicity shift may be caused by a systematic offset in the SSPP. To test this hypothesis, we apply the optimized SSPP to the SEGUE sample of globular and open clusters. NGC 2420, NGC 6791, and M67 have both G- and K-dwarf targets; unfortunately, all three are metal-rich clusters. We extract all targets with  $\log g$  of 4.1 and higher and compare the mean metallicity of targets within the G- and K-dwarf color cuts. For these three clusters, we see a consistent offset of 0.04 dex in  $[\text{Fe}/\text{H}]$ , with K dwarfs being more metal poor. As this comparison is for a small sample size over a less-than-optimal metallicity range, we are not sure whether or not the  $[\text{Fe}/\text{H}]$  offset between G and K dwarfs is real or a systematic shift for the coolest stars in the SSPP. We are currently testing this by comparing the SSPP parameters with a high-resolution

sample.

### 5.3. Spatial Variation

Using the calculated distances, we determine the current Galactic position ( $X$ ,  $Y$ ,  $Z$ ) of all of the stars. Figure 13 shows the volume-complete samples of 7,834 G and 5,407 K dwarfs in  $R$  and  $Z$ . This sample has substantial coverage of the in situ disk, far more than previous spectroscopic surveys, allowing us to constrain the metallicity structure with respect to position.

#### 5.3.1. Radial Metallicity Gradient

As mentioned earlier, various disk formation mechanisms will imprint different chemical structure on the Galactic disk. We first examine the disk abundance structure with respect to radius. Separating our G- and K-dwarf sample into 0.5 kpc increments of  $|Z|$ , we divide the sample at each height into equal-sized bins in  $R$ , based on weighted number, and calculate the median  $R$  and  $[Fe/H]$ . Finally, we perform a linear least squares fit to the median values. The radial gradients for K and G dwarfs is shown in Figure 14 and the slopes are listed in Table 4.

We use a two-pronged approach to estimate the uncertainties for the radial gradients. First, we use a bootstrap analysis to estimate the standard deviation for the medians in  $R$  and  $[Fe/H]$  over 100 iterations, shown in Figure 14. Second, we quantify the effect of correlated errors in  $[Fe/H]$  and distance on our radial gradients. As with the MDF, an underestimate in  $[Fe/H]$  will lead to an underestimated distance, and vice versa, moving targets into different bins of  $R$ ,  $|Z|$ , and  $[Fe/H]$ . Beyond the solar radius, this correlated error will result in a positive slope, whereas in the direction of the Galactic center, it manifests as a negative slope. Our sample is numerically dominated by stars away from the Galactic center; thus these correlated uncertainties will in general induce a positive slope.

We quantify the size of this effect by performing a Monte Carlo analysis on the modeled lines of sight from TRILEGAL. Isolating G and K dwarfs in the TRILEGAL sample, we simulate the SSPP uncertainty in metallicity and quantify the resulting change in distance for each star. As expected, the errors induce a significant positive slope in the modeled sample. We quantify the size of the induced slope in TRILEGAL, listed in Table 4. This value must be removed from our calculated gradients to avoid  $[Fe/H]$ -distance bias.

We analyze the SEGUE sample of G and K dwarfs two ways. First, we calculate the slopes and medians with and without removing the most metal-poor stars. Limiting our sample to stars with  $[Fe/H] > -1.4$  avoids contamination from halo stars, but it also may remove any evidence of a metal-weak thick disk from our sample. The slopes and medians of the two variations all agree within the uncertainties, indicating that the most metal-poor portion of our sample has

little effect on the gradients. Alternatively, we used an outlier rejection process, removing all stars more than  $3\sigma$  from the mean over multiple iterations; this technique produced little change in the estimated radial gradients. For our second analysis of the sample, we calculate the unweighted radial metallicity gradients. The slopes and medians agree with one another within the estimated uncertainties. Although the metallicity distributions change dramatically when we account for the SEGUE target selection biases, it appears to have little effect on the radial metallicity gradient. We also compare the gradients in the G and K dwarfs to each other, finding that the two spectral types are in good agreement with one another in both slope and the median points.

Cheng et al. (2011, C11) have completed a similar analysis for main-sequence turnoff stars on low-latitude SEGUE plates. This sample of hotter stars probe different lines of sight than ours, staying more within the plane of the Galaxy. C11 cover a much larger radial distance than we do, from 5 to 18 kpc at  $|Z|$  of 1.50 kpc; our sample is generally within  $\pm 1$  kpc of the solar neighborhood in  $R$ . The stars themselves also require different analysis techniques, in particular with respect to SEGUE target selection biases, extinction, and estimations of stellar distance. We compare our results with their findings in Figure 14.

The lowest bin in  $|Z|$ , from 0.2 to 0.5 kpc, has large uncertainties in the medians of G dwarfs. There is not a large number of stars that fall within this  $|Z|$  bin from either spectral type, around 200 G and 375 K dwarfs. In particular, there are few G dwarfs within the solar radius, resulting in an increased variation in the median values at low  $R$ . C11 detect a negative radial metallicity gradient for the lowest bin in  $|Z|$ , as indicated by the dotted lines in Figures 14. Our calculated slope is positive (see Table 4); however, when we correct for the correlated metallicity and distance errors, our estimated radial gradients are in agreement with their values within the uncertainties. Independent of this correction, our median points are consistent with the results of C11, despite our more limited range in radius.

From 0.5 to 1.0 kpc in  $|Z|$ , C11 also determine a negative metallicity gradient. As the thin disk is expected to dominate below 1 kpc from the plane of the Galaxy, this suggests that the radial metallicity gradient for this component is negative. Although our original weighted radial gradient is positive, when we correct for the correlated  $[\text{Fe}/\text{H}]$ -distance errors using TRILEGAL, our value of  $-0.02$  dex/kpc is in good agreement with the C11 results of  $-0.013$  dex/kpc. Our median values also align well within the bootstrap uncertainties with their derived slopes for both G and K dwarfs.

Above  $|Z|$  of 1 kpc, the thick disk is expected to dominate. C11 observe a transition in their radial metallicity gradient; above this height, they detect a flat metallicity gradient. Once again, our median values are in agreement with their derived slopes. Furthermore, when we factor in our bias in slope, we observe a radial metallicity gradient of  $\sim 0$ , matching their detection. The C11 sample does not probe beyond a  $|Z|$  of 1.5 kpc. At this distance from the plane, the G dwarfs exhibit a radial gradient of  $\sim 0$  dex/kpc. The radial metallicity gradient for K dwarfs at this height is consistent with being flat, albeit with large uncertainties, as there are only around 180 K dwarfs

at this height.

Beyond the SEGUE sample, recent work by Coşkunoğlu et al. (2011) estimated the radial metallicity gradient of a sample of 17,000 F and G dwarfs from the RAdial Velocity Experiment (RAVE). The youngest subsample of stars, representative of the thin disk, has a metallicity gradient of  $-0.051 \pm 0.005$  dex  $\text{kpc}^{-1}$ , comparable to the low  $|Z|$  value found by C11 and in agreement with our estimated slopes below  $|Z|$  of 0.5. The dwarfs from this sample do not extend beyond 300 pc from the Sun, making it difficult to constrain the radial  $[\text{Fe}/\text{H}]$  structure of the thick disk.

Although we cover a much more limited range in  $R$  than the sample of C11, we find good agreement with their estimated radial metallicity gradients, in addition to the calculations from Coşkunoğlu et al. (2011). The radial gradient in the G and K dwarfs appears to transition from a negative to flat slope around  $|Z|$  of 1 kpc, suggesting that the thin and thick disk exhibit different radial metallicity structure. This implies that the two components may have had different formation and evolution processes. We are currently working to separate the thin and thick disk chemically and kinematically to compare the gradients in individual components to formation models. Our current analysis for the disk as a whole indicates that our methodologies accurately predict the radial gradient, despite our samples' limited coverage in  $R$ .

#### 5.4. Vertical Metallicity Gradient

Our G- and K-dwarf sample probes far above and below the Galactic plane; Figure 15 shows the distribution of stars with respect to  $[\text{Fe}/\text{H}]$  and distance from the plane, using the spectral type distance ranges for G and K dwarfs. We bin the sample in  $|Z|$  and  $[\text{Fe}/\text{H}]$ , adjusting each bin with the target-selection weights for each individual star. The colors represent the logarithm of the weighted number of stars in each bin. The black points are the median  $[\text{Fe}/\text{H}]$  and  $|Z|$  in 10 bins of equal weighted size; the uncertainties are the standard deviation on the median values from a bootstrap analysis over 100 iterations. For these median values, we limit the sample to stars with  $[\text{Fe}/\text{H}] > -1.4$ , to avoid significant halo contamination.

Although our distribution in  $[\text{Fe}/\text{H}]$  and  $|Z|$  shows a similar pattern that of Ivezić et al. (2008) and Bond et al. (2010) for the SDSS photometric sample, there is an offset in the metallicity. Our sample is more metal rich by approximately 0.2 dex. This discrepancy may stem from systematic offsets between the SSPP metallicities and those determined using photometric indicators. In addition, although our magnitude-limited sample has few stars below  $|Z|$  of 0.2 kpc, our relation suggests that the metallicity of the solar-neighborhood is more metal poor than the Sun.

We divide the sample into bins of  $|Z|$  and examine the distribution of  $[\text{Fe}/\text{H}]$  at each height above the plane in Figure 16 (see Tables 5, 6, 7, 8). The G- and K-dwarf sample here is limited to the volume-complete distance range. Both the G and K dwarfs show a small metal-poor tail at all  $|Z|$ ; whether this tail stems from halo contamination or a metal-weak thick disk is currently unclear (Beers et al. 2002). Although they agree within the uncertainties, the tail in K dwarfs is



slightly larger. As observed in the total distribution (Figure 12), the K dwarfs also exhibit a shift to more metal-poor values than the G dwarfs. However, both spectral types generally cover the same metallicity range and peak at comparable  $[\text{Fe}/\text{H}]$ .

As it is less likely than kinematics to change significantly over time, stellar chemistry is a useful diagnostic to disentangle the thin and thick disk. Lee et al. (2011b) use the  $[\alpha/\text{Fe}]$  ratios of the SEGUE G-dwarf stars to separate the thin- and thick-disk components. They use a slightly different G-dwarf sample than ours, with  $S/N > 30$ ,  $\log g \geq 4.2$ , and distances within 3 kpc. They also do not weight their sample to account for target selection biases. We compare our G-dwarf metallicity distribution over the spectral distance range to the  $\alpha$ -poor and  $\alpha$ -enhanced metallicity distributions in Figure 17. For both G and K dwarfs, the peak metallicity shifts to smaller values as  $|Z|$  increases. The  $\alpha$ -poor, metal-rich thin disk dominates between  $|Z|$  of 0.1 and 0.5 kpc. At  $|Z|$  of 1.0 kpc, Lee et al. (2011b) observe that the  $\alpha$ -enhanced, metal-poor component begins to dominate. This result implies that above 1.0 kpc in  $|Z|$ , our G- and K-dwarf sample is dominated by thick-disk stars, confirming that our observed vertical metallicity gradient reflects the transition from thin to thick disk, rather than a change in the metallicity of an individual component with respect to distance from the plane.

We adapt the methodology used to determine the radial metallicity gradient to directly calculate the vertical metallicity gradient. We divide the sample into 10 bins of equal-weighted number and calculate the median  $[\text{Fe}/\text{H}]$  and  $|Z|$  for each bin, shown in Figure 18, fitting the values with a linear least squares fit. As with the radial gradient, we must also take into account the correlated errors in metallicity and distance. For the radial metallicity gradient, these uncertainties shift stars in the highest  $|Z|$  bin to higher metallicities and stars in the lowest  $|Z|$  bin toward the more metal-poor end. This effect will camouflage any existing slope with respect to distance from the plane. We estimate the size of this effect using TRILEGAL-modeled lines of sight, finding that the correlated uncertainties induce a positive slope of  $\sim 0.25$  dex/kpc (Table 9).

Past work by Katz et al. (2011) sought to constrain the vertical metallicity gradient of the thick disk. Their sample consists of approximately 400 stars along two lines of sight; they calculate atmospheric parameters using the ETOILE spectral matching program. Utilizing a series of Besançon Galaxy models, they distinguish the thick-disk stars from the thin-disk population. In their extracted thick-disk sample, Katz et al. (2011) detect a small vertical metallicity gradient with  $\delta[\text{Fe}/\text{H}]/\delta|Z|$  of  $-0.068 \pm 0.009$  dex kpc $^{-1}$ . We apply our gradient technique to their entire sample for a direct comparison of disk structure; we do not extract the thick-disk component as in their paper. Our method results in a larger gradient,  $-0.11$  dex/kpc, for the disk as a whole (represented by the gray points with uncertainties derived from a bootstrap analysis in Figure 18), than they report for the thick disk alone. Due to the larger size of our sample, the uncertainties on the SEGUE G- and K-dwarf medians are much smaller than those from Katz et al. (2011). We do not currently estimate the size of any induced slope from uncertainties for the Katz et al. (2011) sample with TRILEGAL, as we cannot accurately simulate and account for their target-selection effects.

For both G and K dwarfs, we estimate a vertical metallicity gradient of approximately  $-0.3$  dex/kpc. Factoring in the bias from correlated  $[\text{Fe}/\text{H}]$ -distance uncertainties, this value increases to  $-0.6$  dex/kpc. The medians of Katz et al. (2011) and our G- and K-dwarf sample agree within the uncertainties at low  $|Z|$ . However, they become increasingly discrepant at greater heights above the plane, resulting in different slopes (Fig. 18, Table 9).

Although the medians of our G- and K-dwarf sample are often distinct from those of Katz et al. (2011), the distributions with respect to  $|Z|$  are consistent (Figure 19). The samples agree well between  $|Z|$  of 0.5 and 1.5 kpc. For the lowest bin in  $|Z|$ , their distribution is more metal poor than ours. At the highest range in  $|Z|$ , their distribution is more metal rich than the SEGUE G and K dwarfs. The Katz et al. (2011) sample is limited to only two lines of sight; it is unclear how well their sample reflects the overall disk structure.

Recent work by Kordopatis et al. (2011) on 700 F, G, and K dwarfs found a vertical gradient of  $-0.14 \pm 0.05$  dex/kpc for the thick disk, isolating the component spatially. This value is larger than that of the Katz et al. (2011) sample for the thick disk and comparable to the value we determine with these stars for the disk as a whole. Chen et al. (2010, 2011) find a larger gradient value studying red horizontal branch stars from SDSS DR7 and DR8; linearly fitting the data, they estimate a thick-disk vertical metallicity gradient of  $-0.225 \pm 0.07$  dex/kpc. When they utilize the Besançon Galaxy model (Robin et al. 2003) to isolate the thick disk, this slope diminishes to  $-0.12 \pm 0.01$  dex/kpc. All of these works exhibit some negative vertical gradient for the thick disk, although the actual value is debated. We are currently working to isolate the thick-disk component via stellar chemistry, which will allow us to estimate the vertical gradient independent of spatial or model assumptions. Our large in situ sample of G and K dwarfs will allow us to determine these properties with unprecedented accuracy.

## 5.5. Comparison with Models

The G- and K-dwarf MDFs are a valuable test for the different Galaxy chemical and dynamical evolution models. Current models are chemically calibrated on previous observational work, namely the GCS sample (Jørgensen 2000; Nordström et al. 2004; Casagrande et al. 2011), which is limited to the solar neighborhood. We compare our MDFs to various models to examine their accuracy beyond the local volume.

### 5.5.1. Comparison with the Simple Closed Box Model

The G-dwarf problem stemmed from the observational results that a simple closed box model of chemical evolution overpredicted the number of metal-poor stars (van den Bergh 1962; Wyse & Gilmore 1995; Rocha-Pinto & Maciel 1996; Favata et al. 1997). In the top row of Figure 20, we compare our distribution of G and K dwarfs to a simple closed box model with instantaneous recycling, based

on that of Pagel (1997). As expected, we find that our empirical distributions of both G and K dwarfs are deficient at the low-metallicity end when compared to these models, confirming that the G-dwarf problem is present in the SEGUE sample and persists to lower temperatures. For the total sample, the fraction of K stars with  $[\text{Fe}/\text{H}]$  less than  $-0.8$  is  $\sim 21\%$ , whereas the model predicts  $28\%$ . Similarly, the model predicts  $27\%$  of G dwarfs should have  $[\text{Fe}/\text{H}] < -0.8$ , but we observe  $\sim 18\%$ .

The G-dwarf problem was originally reported for stars within the solar neighborhood. We also detect it for both G and K dwarfs at a range of distances from the plane (Figure 20). The discrepancies range from  $6\text{--}15\%$  between the observed distribution and the simple closed box model, are enhanced at larger distances from the plane, and are generally consistent between the spectral types. Existing chemical evolution models are constrained by solar-neighborhood samples and tend to be more metal rich than our sample; this makes it difficult to do a direct comparison and test the different predictions. However, our distributions allow modelers to examine the star formation history of the disk far beyond our local volume.

### 5.5.2. Comparison with Galaxy Models

We compare the G-dwarf metallicity distribution to the SB and TRILEGAL Galaxy models in Figures 21 and 22 respectively. For both models, we combine all of the SEGUE-modeled lines of sight. We then extract simulated stars that fulfill the color, magnitude, and distance criteria for our G-dwarf spectral type.

Figures 21 and 22 indicate that the metallicity range of the different samples is in general agreement for the lowest bin in  $|Z|$ , although both models tend to be more metal rich and sharply peaked than the SEGUE sample. The narrower peak is likely a consequence of the broadening effect from correlated  $[\text{Fe}/\text{H}]$ -distance errors (see § 5.1). At higher distances from the plane, the metallicity discrepancy between the models and the SEGUE sample increases. Whereas the SEGUE distributions shift towards more metal-poor values, the models remain at an  $[\text{Fe}/\text{H}]$  of  $-0.1$  for SB and  $-0.3$  for TRILEGAL. In fact, the SB distributions become slightly more metal rich at greater distances from the plane. Neither model predicts the significant metal-poor population in G dwarfs that we observe. We find the same discrepancies for the K-dwarf sample.

The SB models are calibrated in  $[\text{Fe}/\text{H}]$  using the GCS sample (Nordström et al. 2004; Holmberg et al. 2007; Casagrande et al. 2011). By analyzing the kinematics of the GCS sample, specifically the  $|W|$  Galactic space velocity, one can isolate the various structural components of the Milky Way. With increasing  $|W|$ , which implies moving from the thin to the thick disk and then the halo, there is a very weak metallicity gradient in the GCS sample. The peak metallicity remains at around  $[\text{Fe}/\text{H}] = -0.2$ , in contrast to the clear thin/thick disk transition we observe. Thus, the SB models show little transition in  $[\text{Fe}/\text{H}]$  with respect to  $|W|$  as well.

Beyond GCS, Schönrich & Binney (2009b) compare their model predictions to various observed

samples, such as Fuhrmann (1998), Bensby et al. (2003), Reddy et al. (2006), and Haywood (2008), to constrain chemical parameters. Although many of these samples contain thick-disk stars, they are all limited to the solar neighborhood, which is thin-disk dominated. The GCS sample is typically within 200 pc (Casagrande et al. 2011). Similarly, the farthest distance probed by the Reddy et al. (2006) sample, which was selected based on Hipparcos data, is 150 pc. When we compare the SB models with the  $\alpha$ -separated stellar populations from Lee et al. (2011b), the models agree well with the  $\alpha$ -poor thin-disk distribution alone. It is not surprising that the SB models are currently unable to predict the chemical structure of the thick-disk component, as it is calibrated on thin-disk-dominated stellar samples. In an upcoming work, we determine the kinematics and orbital parameters for our G- and K-dwarf stars. With these values, we can perform a direct comparison with the GCS to further quantify the difference between these two samples.

The discrepancies observed in the SB Galaxy model are also evident in the TRILEGAL comparison. Figure 22 indicates that the TRILEGAL model accurately predicts the  $\alpha$ -poor disk component, but not the more metal-poor, thick-disk population. Although TRILEGAL exhibits excellent agreement with different components of the Galaxy with respect to stellar counts (Girardi et al. 2005), there has been little chemical testing of the models. It is promising that the modeled halo component, chemically calibrated with Ryan & Norris (1991), exhibits good agreement with our observed metal-poor tail.

Finally, we also see discrepancies with the Besançon Galaxy model (Robin et al. 2003, personal communication). As with the SB and TRILEGAL models, the sample is more metal poor than the models at large  $|Z|$ . All three of these models are calibrated on local data, which reveals little information far beyond the plane of the Galaxy. Combined with the current confusion about the early moments of disk formation, this results in models that are currently not accurately predicting the thick-disk structure.

## 6. Summary

In this work we utilize the SEGUE G- and K-dwarf sample to examine the variation in metallicity with respect to position in the Galaxy. We optimize the SSPP to better handle low-temperature dwarfs and develop a multifaceted approach to account for target-selection biases in the SEGUE sample, using SDSS photometry for each individual line of sight. This technique increases the proportion of metal-rich stars in the sample and is critical for accurately constraining the metallicity structure of the Milky Way disk. We also examine smaller biases, such as contamination by undetected binaries and subgiants.

Using an isochrone matching technique, we calculate distances accurate to  $\sim 12\%$  for all of our G and K dwarfs. This allows us to define a volume-complete sample. Using our various target-selection weights, we determine the total MDFs of the G- and K-dwarf samples (Fig. 12), estimating the error in each  $[\text{Fe}/\text{H}]$  bin via a bootstrap algorithm. The total MDFs of both the G- and K-dwarf

samples peak at  $[\text{Fe}/\text{H}]$  of around  $-0.5$  dex, implying we have a substantial population of thick-disk stars in our sample. The two spectral types cover a similar range in metallicity, although the K dwarfs show a more prominent metal-poor tail. The MDFs of both G and K dwarfs find fewer metal-poor stars than predicted by a simple closed box model (Fig. 20). This is consistent with previous work, such as Mould (1982), Favata et al. (1997), Flynn & Morell (1997), Rocha-Pinto & Maciel (1998), and Kotoneva et al. (2002), which found that the G-dwarf problem persists down to cooler temperatures. Furthermore, we establish that the G- and K-dwarf problem is found beyond the solar neighborhood.

In addition to the total MDF, we use our distances to examine the metallicity with respect to different  $R$  and  $|Z|$ . This is particularly useful for constraining different models of disk formation, which provide various predictions of radial and vertical metallicity gradients. In four bins of  $|Z|$ , we calculate the radial metallicity gradient for G and K dwarfs (Figs. 14). Although we cover a much smaller radial distance, our weighted slopes and medians are in agreement with those calculated in Cheng et al. (2011), and we are consistent with their results of a small negative metallicity gradient for low  $|Z|$  that flattens out at  $|Z| \geq 1.0$  kpc. Cheng et al. (2011) suggest that the lack of a radial metallicity gradient indicates that the thick disk is chemically homogeneous, favoring the thick-disk formation scenario of rapid star formation in an early turbulent disk phase. This model also supports thick-disk formation via radial migration, which would wash out any pre-existing radial metallicity gradient. Observations of similar radial structure support this theory, but, with our uncertainties, we cannot currently rule out other proposed formation scenarios.

We also examine the metallicity distribution of G and K dwarfs with respect to the distance from the plane. Both spectral types exhibit a decrease in the peak metallicity as  $|Z|$  increases. In addition, the peak  $[\text{Fe}/\text{H}]$  of the G- and K-dwarf distributions in different ranges of  $|Z|$  agree within the calculated uncertainties (Fig. 16, Tables 5, 6, 7, and 8), implying similar star-formation history. Based on the metal-poor,  $\alpha$ -enhanced definition of the thick disk (Bensby et al. 2003, 2005; Lee et al. 2011b), this vertical metallicity gradient represents the transition between a thin- and thick-disk population. We also compare our samples to that of Katz et al. (2011). Their sample is limited in both area and number. They detect a slope of around  $-0.1$  dex/kpc, smaller than ours of  $-0.3$  dex/kpc. Although the slopes are discrepant, their metallicity distributions show reasonable agreement with ours between  $|Z|$  of 0.5 and 1.5 kpc (Figure 18, 19).

Our detection of a slight vertical metallicity gradient in both our G- and K-dwarf samples is not predicted by the SB or TRILEGAL Galaxy models. In fact, our distributions only agree with these models in the lowest range of  $|Z|$ , in the realm of the solar neighborhood. Both models predict only the  $\alpha$ -poor thin-disk component of the Galaxy, because their primary chemical calibration has been based on solar neighborhood samples. Thus, our observed thin-to-thick disk transition and distributions provide a valuable constraint on future Galaxy formation and evolution models. In upcoming work, we will perform a dynamical analysis of the SEGUE G- and K-dwarf sample. In conjunction with abundance information, we can isolate the thick disk from the thin disk to compare directly with formation models.

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## A. Uncertainties in Calculated Distances

### A.1. Random Error in Distance Calculations

Our two isochrone distances have random errors that are dominated by uncertainties in the SSPP. This pipeline has well-established uncertainties at a range of  $S/N$ , as described in Lee et al. (2008a). We also must take into account the photometric errors of SDSS.

#### A.1.1. $[Fe/H]$ Errors

The SSPP provides  $[Fe/H]$  uncertainties for each spectroscopic target; these values quantify the random error. To conservatively estimate the total  $[Fe/H]$  error, we combine these uncertainties in quadrature with the maximum reported uncertainty from the SSPP in  $[Fe/H]$ ,  $\pm 0.45$  dex (Lee et al. 2008a). To estimate the distance uncertainty from the isochrone method, we compare the  $(g-r)_0$  of the target to isochrones of the minimum and maximum possible  $[Fe/H]$ . For both isochrone types, the distance uncertainty stemming from metallicity is approximately  $8\pm 5\%$ .

### *A.1.2. Photometric Errors*

The photometric uncertainty of SDSS targets is typically 2-3%. For the two isochrone methods, the photometric errors must be accounted for twice; first, when we match each target to an isochrone in  $(g-r)_0$  and second, when we calculate the distance in each individual filter. Using the reported SDSS uncertainties, we determine a mean percentage uncertainty in isochrone distance from photometric errors of  $\sim 2\%$ .

### *A.1.3. $[\alpha/\text{Fe}]$ Uncertainty*

Lee et al. (2011a) found that for a  $S/N > 20$ , the SSPP can determine  $[\alpha/\text{Fe}]$  with an uncertainty of approximately 0.1 dex. At lower  $S/N$ , the uncertainty increases to 0.2 dex. Variation within this parameter will shift the isochrone, especially for the metal-rich regime. Each isochrone has an assumed  $[\alpha/\text{Fe}]$ . These values may not align with the  $[\alpha/\text{Fe}]$  of the individual target. To estimate the uncertainty associated with this effect, we compare our Dartmouth isochrones with  $[\alpha/\text{Fe}]$  of 0 to those with  $[\alpha/\text{Fe}]$  of +0.2 and  $-0.2$  dex. Using the conservative assumption of  $\sigma_\alpha$  of 0.2, we find that variations in  $[\alpha/\text{Fe}]$  will result in a  $\sim 4\%$  distance uncertainty.

## **A.2. Systematic Uncertainties in Distance Calculations**

### *A.2.1. Uncertainties from Binarity*

If a target is part of a binary, this will drastically change the distance calculated for the star. An undetected secondary star will make the primary appear brighter; consequently, we will underestimate the distance. Using the techniques described in Schlesinger et al. (2010), we model a population of binaries, using a Chabrier IMF (Chabrier 2003) for the primaries and a Halbwachs  $q$  distribution for the secondaries (Halbwachs et al. 2003). This secondary distribution boosts the expected number of binaries where both members are of similar mass; thus, it will result in the largest effect on distances. For this simulated population of binaries, the change in magnitude due to a secondary is strongly peaked at 0, with a  $\sigma$  of approximately 0.24 mag; this corresponds to an uncertainty of around 11% in distance. As approximately 65% of all G and K stars are in binaries (Duquennoy & Mayor 1991), this results in an overall distance uncertainty of around 7%.

In addition to affecting photometry, undetected pairs can also alter our distance measurements via changes in the metallicity determination. The expected  $[\text{Fe}/\text{H}]$  uncertainty at a  $S/N$  of 25 is  $\pm 0.30$  dex. Schlesinger et al. (2010) find that around 95% of all pairs will have a shift in  $[\text{Fe}/\text{H}]$  less than 0.15 dex. Thus, distance uncertainties stemming from a secondary’s effect on  $[\text{Fe}/\text{H}]$  determinations are well within the error expected from the SSPP  $[\text{Fe}/\text{H}]$  determination, and we do not take them into account individually.

### *A.2.2. Age Effects on Distance Calculations*

To calculate distances, we assume all stars have an age of 10 Gyr and compare them to isochrones of the same age. However, the actual ages of these stars are unknown. In particular, the most metal-rich stars are likely significantly younger than this value, causing a systematic overestimate of the distances.

To estimate the uncertainty from age in our isochrone methods, we compare the calculated distances under various age assumptions. We calculate the distance for each star assuming a much smaller age, from 1 to 5 Gyr, depending on the metallicity. For each star, we linearly interpolate between the 10 Gyr and younger isochrones and determine the error in parameters and distance that results from an assumed 20% error in age. The expected magnitude offset from this is around 0.02 mag, corresponding to around 1% distance uncertainty. As all of our targets are on the main sequence it is not surprising that we see little effect with respect to age assumptions. At this point in stellar evolution, isochrones of a given metallicity overlap quite closely.

### *A.2.3. Uncertainty from Isochrone Choice*

Each individual isochrone set will yield a slightly different  $ugriz$  values at the same  $(g - r)$ , resulting in systematic differences in distance with respect to one another. Distances calculated using YREC isochrones tend to be smaller than those calculated via Dartmouth isochrones by around  $5 \pm 7\%$ . Comparison with Padova and BASTI isochrones yield differences of a similar order of magnitude.

## **B. Constraining distance uncertainties using Galaxy models**

A complete test of our distance calculations requires a large sample of main-sequence targets over a range of metallicity and ages at known distances. As we do not have an appropriate spectroscopic sample, we test our methodologies using theoretical Galaxy models from TRILEGAL (§3.4.1) and SB (§3.4.2). These two models are based on different isochrones, allowing us to further constrain the effect of isochrone choice. Additionally, they cover a range of ages, allowing us to test the uncertainty from our age assumptions. Finally, the BASTI isochrones in the model are artificially broadened to simulate the SDSS errors in photometry, providing a good estimate of our overall distance uncertainty.

The two Galaxy models provide age, metallicity, mass,  $ugriz$  magnitudes, and distances for individual lines of sight. To simulate our G-K dwarf sample in SEGUE, we extract every target with a metallicity between 0.4 and  $-3.5$ ,  $(g - r)$  color within the G-K dwarf range, and a surface gravity greater than or equal to 4.1, to ensure that they are on the main sequence. As with the SEGUE sample, we calculate the distances of our simulated targets using both the Dartmouth



and YREC isochrones. Figures 23 and 24 present the distances calculated by our two different isochrone sets for a TRILEGAL and SB line of sight, respectively.

The Dartmouth isochrone methods tend to overestimate the model distances, by 4% in the TRILEGAL and 10% in SB. In contrast, the YREC isochrone method tends to underestimate distances for both Galaxy models. For the TRILEGAL model, the most frequent shift is approximately  $-4\%$ . The YREC isochrones fall in line more with the broadened BASTI isochrones, resulting in a fractional difference of around  $-1.5\%$ . These systematic shifts reflect the different isochrone systems used to create the models and calculate the distances. Overall, isochrone choice will add a systematic shift to the order of 9% in distance.

We can also use our Galaxy models to quantify the uncertainty from our age assumption. Rather than calculating distances by matching to 10 Gyr isochrones in metallicity, we match each target to the isochrone closest in metallicity *and* age. We compare the calculated values for a particular line of sight in the SB models in Fig. 25. The bottom row of the figure compares the distance assuming 10 Gyr to that matching each target in age; the percent difference has a mean of  $1\pm2\%$  for YREC isochrones. Comparison with Dartmouth isochrones, and testing on TRILEGAL models, yielded similar results.

The age uncertainty from linear interpolation and Galaxy models agree well with each other. Both reveal that the uncertainty is larger at the metal-rich end, as expected, ranging from around 3% at  $[\text{Fe}/\text{H}] \geq 0$  to less than 1% at  $[\text{Fe}/\text{H}]$  of  $-2.0$ . These uncertainties are quite small overall. Thus, we feel confident that assuming each target has an age of 10 Gyr will not significantly affect our distance calculations.

Finally, we use the SB Galaxy models to estimate the overall uncertainty in our distance calculations, as this model has simulated photometric and metallicity errors comparable to those in SEGUE. Propagation of errors predicts an expected random error of approximately 10%, factoring in uncertainties from metallicity, photometry, and  $[\alpha/\text{Fe}]$ , with an additional uncertainty from systematics of around 8%. Thus, the total distance uncertainty from the isochrone techniques is typically around 12%, which is in good agreement with the percent difference of distances we calculate for the SB model.

### C. Distances from Photometric Parallax

Ivezić et al. (2008) develop a photometric parallax relationship which takes into account metallicity, building upon the work by Jurić et al. (2008). The shape of the photometric relationship is based on SDSS observations of five globular clusters: M2, M3, M5, M13, and M15. These clusters range from 7 to 12 kpc in distance and  $-1.2$  to  $-2.1$  in  $[\text{Fe}/\text{H}]$  (Harris 1996). Using clusters from Vandenberg & Clem (2003), which range from  $-2.5$  to  $+0.12$  in  $[\text{Fe}/\text{H}]$ , they then constrain the extent of magnitude shifts for different metallicities. Combining the equations determined for

different ranges in  $(g - i)$ , their final relationship is as follows:

$$M_r(g - i, [Fe/H]) = M_r^0(g - i) + \Delta M_r([Fe/H]) \quad (C1)$$

$$M_r^0(g - i) = -5.06 + 14.32(g - i) - 12.97(g - i)^2 + 6.127(g - i)^3 - 1.267(g - i)^4 + 0.0967(g - i)^5 \quad (C2)$$

$$M_r([Fe/H]) = 4.50 - 1.11[Fe/H] - 0.18[Fe/H]^2 \quad (C3)$$

Ivezić et al. (2008) specify that these equations are valid for dwarfs with  $0.2 < (g - i) < 4.0$ . Less than 1% of G and K dwarfs fall outside of this color range. They expect uncertainties of around 5% and 10-15% from systematic and random errors, respectively (Bond et al. 2010).

We compare our YREC isochrone distances to those calculated using photometric parallax, finding an offset of approximately 8%, with YREC distances typically smaller. This result is due to a typical 0.2 mag offset between the YREC isochrones and photometric metallicity relations. Similar offsets are found with the BASTI and Padua isochrones. The difference is slightly less for the Dartmouth isochrones. When we calculate distances for the two Galaxy models, we find 10-15% larger distances using the photometric parallax relationship. Despite this discrepancy, the mean photometric parallax distances for our sample of open and globular clusters are consistent with both literature values and those from the isochrones (see Table 2, Fig. 9).

We choose to use YREC isochrones for three reasons. First, the photometric parallax relationship is calibrated on distances from Harris (1996). Analysis in the interim has found significant variation in these calculated distances, increasing the uncertainty of the calibration, e.g., Table 2 in An et al. (2009). Second, the photometric parallax dependence on metallicity uses clusters that were not observed in *ugriz* photometry. The conversion from Johnson-Cousins to *ugriz* is uncertain. Finally, as with the Dartmouth isochrones, the photometric parallax relationship is calibrated only to  $[Fe/H]$  of  $-2.5$ , whereas the YREC isochrones go down to  $-3.0$ . To ensure our distance method does not significantly change our results, we have also calculated the metallicity distribution functions using photometric parallax distances instead of those from YREC. There are only slight changes, all of which are well within the expected bootstrap uncertainties for the distributions and gradients.

## REFERENCES

- Abadi, M. G., Navarro, J. F., Steinmetz, M., & Eke, V. R. 2003, *ApJ*, 597, 21
- Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., Allam, S. S., Allende Prieto, C., An, D., Anderson, K. S. J., & et al. 2009, *ApJS*, 182, 543
- Aihara, H., Allende Prieto, C., An, D., Anderson, S. F., Aubourg, É., Balbinot, E., Beers, T. C., Berlind, A. A., et al. 2011, *ApJS*, 193, 29
- Allende Prieto, C., Beers, T. C., Wilhelm, R., Newberg, H. J., Rockosi, C. M., Yanny, B., & Lee, Y. S. 2006, *ApJ*, 636, 804

- Allende Prieto, C., Sivarani, T., Beers, T. C., Lee, Y. S., Koesterke, L., Shetrone, M., Sneden, C., Lambert, D. L., Wilhelm, R., Rockosi, C. M., Lai, D. K., Yanny, B., Ivans, I. I., Johnson, J. A., Aoki, W., Bailer-Jones, C. A. L. & Re Fiorentin, P. 2008, *AJ*, 136, 2070
- Alvarez, R. & Plez, B. 1998, *A&A*, 330, 1109
- An, D., Pinsonneault, M. H., Masseron, T., Delahaye, F., Johnson, J. A., Terndrup, D. M., Beers, T. C., Ivans, I. I., & Ivezić, Ž. 2009, *ApJ*, 700, 523
- Arnadottir, A. S., Feltzing, S., & Lundstrom, I. 2009, *IAU Symposium*, 254, 5
- Aumer, M. & Binney, J. J. 2009, *MNRAS*, 397, 1286
- Beers, T. C., Drilling, J. S., Rossi, S., Chiba, M., Rhee, J., Führmeister, B., Norris, J. E., & von Hippel, T. 2002, 124, 931
- Bensby, T., Feltzing, S., & Lundström, I. 2003, *A&A*, 410, 527-551
- Bensby, T., Feltzing, S., Lundström, I., & Ilyin, I. 2005, *A&A*, 433, 185-203
- Bird, J. C., Kazantzidis, S., & Weinberg, D. H. 2011, arXiv, 1104.0933
- Bond, N. A. et al. 2010, *ApJ*, 716, 1
- Bournaud, F., Elmegreen, B. G., & Martig, M. 2009, *ApJ*, 707, L1
- Breddels, M. A., Smith, M. C., Helmi, A. et al. for the RAVE Survey 2010, *A&A*, 511, A90
- Brook, C. B., Kawata, D., Gibson, B. K., & Freeman, K. C. 2004, *ApJ*, 612, 894
- Brook, C. B., Gibson, B. K., Martel, H., & Kawata, D. 2005, *ApJ*, 630, 298
- Brunetti, M., Chiappini, C., & Pfenniger, D. 2011, *A&A*, 534, 75
- Burstein, D. 1979, *ApJ*, 234, 829
- Casagrande, L., Schönrich, R., Asplund, M., Cassisi, S., Ramírez, I., Meléndez, J., Bensby, T., & Feltzing, S. 2011, *A&A*, 530, A138+
- Cassisi, S., Pietrinferni, A., Salaris, M., Castelli, F., Cordier, D., & Castellani, M. 2006, *Mem. Soc. Astron. Italiana*, 77, 71
- Chabrier, G. 2003, *PASP*, 115, 763
- Chen, Y. Q., Zhao, G., Zhao, J. K., Xue, X. X., & Schuster, W. J. 2010, *AJ*, 140, 500
- Chen, Y. Q., Zhao, G., Carrell, K., & Zhao, J. K. 2011, *AJ*, 142, 184
- Cheng, J. Y., Rockosi, C. M., Morrison, H. L., Schönrich, R. A., Lee, Y. S., Beers, T. C., Bizyaev, D., Pan, K., & Schneider, D. P. 2011, arXiv, 1110.5933

- Chiappini, C., Matteucci, F., & Gratton, R. 1997, *ApJ*, 477, 765
- Chiappini, C., Matteucci, F., & Padoan, P. 2000, *ApJ*, 528, 711
- Chiappini, C., Matteucci, F., & Romano, D. 2001, *ApJ*, 554, 1044
- Chiba, M. & Beers, T. C. 2000, *AJ*, 119, 2843
- Coskunoglu, B., Ak, S., Bilir, S., Karaali, S., Onal, O., Yaz, E., Gilmore, G., & Seabroke, G. M. 2011, arXiv, 1109.6519
- Dalcanton, J. J. & Bernstein, R. A. 2002, *AJ*, 124, 1328
- Dotter, A., Chaboyer, B., Jevremović, D., Kostov, V., Baron, E. & Ferguson, J. W. 2008, *ApJS*, 178, 89
- Duquennoy, A. & Mayor, M. 1991, *A&A*, 248, 485
- Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, *A&A*, 275, 101
- Eisenstein, D. J., Weinberg, D. H., & Agol, E. et al. 2011, *AJ*, 142, 72
- Elmegreen, B. G. & Elmegreen, D. M. 2006, *ApJ*, 650, 644
- Favata, F., Micela, G., & Sciortino, S. 1997, *A&A*, 323, 809
- Flynn, C., & Morell, O. 1997, *MNRAS*, 286, 617-625
- Friedli, D., Benz, W., & Kennicutt, R. 1994, *ApJ*, 430, L105
- Fuchs, B. 2001, *MNRAS*, 325, 1637
- Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, *AJ*, 111, 1748
- Fuhrmann, K. 1998, *A&A*, 338, 161
- Gilmore, G. & Reid, N. 1983, *MNRAS*, 202, 1025-1047
- Gilmore, G. & Wyse, R. F. G. 1985, *AJ*, 90, 2015
- Girardi, L., Grebel, E. K., Odenkirchen, M., & Chiosi, C. 2004, *A&A*, 422, 205-215
- Girardi, L., Groenewegen, M. A. T., Hatziminaoglou, E., & da Costa, L. 2005, *A&A*, 436, 895
- Grevesse, N., Asplund, M., & Sauval, A. J., 2007, *Space Sci. Rev.*, 130, 105
- Gunn, J. E., Carr, M. A., Rockosi, C. M., Sekiguchi, M., et al. 1998, *AJ*, 116, 3040

- Gunn, J. E., Siegmund, W. A., Mannery, E. J., Owen, R. E., et al. 2006, *AJ*, 131
- Gustafsson, B., Edvardsson, B., Eriksson, K., Jørgensen, U. G., Nordlund, Å., & Plez, B. 2008, *A&A*, 486
- Halbwachs, J. L., Mayor, M., Udry, S. & Arenou, F. 2003, *A&A*, 397, 159
- Harris, W. E. 1996, *AJ*, 112, 1487
- Haywood, M. 2008, *MNRAS*, 388, 1175
- Hogg, D. W., Finkbeiner, D. P., Schlegel, D. J., & Gunn, J. E. 2001, *AJ*, 122, 2129
- Holmberg, J., Nordström, B., & Andersen, J. 2007, *A&A*, 475, 519
- Holmberg, J., Nordström, B., & Andersen, J. 2009, *A&A*, 501, 941
- Ivezić, Ž, Lupton, R. H., Schlegel, D., et al. 2004, *Astronomische Nachrichten*, 325, 583
- Ivezić, Ž. et al. 2008, *ApJ*, 684, 287
- Jacobson, H. R., Pilachowski, C. A., & Friel, E. D. 2011, *AJ*, 142, 59
- Jørgensen, B. R. 2000, *A&A*, 363, 947-957
- Jurić, M. et al. 2008, *ApJ*, 673, 864
- Katz, D., Soubiran, C., Cayrel, R., Barbuy, B., Friel, E., Bienaymé, O., & Perrin, M.-N. 2011, *A&A*, 525, A90+
- Kazantzidis, S., Bullock, J. S., Zentner, A. R., Kravtsov, A. V., & Moustakas, L. A. 2008, *ApJ*, 688, 254
- Kennicutt, Jr., R. C. et al. 1998, *ApJ*, 498, 181
- Kordopatis, G., Recio-Blanco, A., de Laverny, P., Gilmore, G., Hill, V., Wyse, R. F. G., Helmi, A., Bijaoui, A., Zoccali, M., & Bienaymé, O. 2011, *arXiv*, 1110.5221
- Kotoneva, E., Flynn, C., Chiappini, C., & Matteucci, F. 2002, *MNRAS*, 336, 879-891
- Kraft, R. P. & Ivans, I. I. 2003, *PASP*, 115, 143-169
- Larson, R. B. 1972, *Nature*, 236, 21
- Larson, R. B. 1976, *MNRAS*, 176, 31
- Lee, Y. S., Beers, T. C., Sivarani, T., Allende Prieto, C., Koesterke, L., Wilhelm, R., Re Fiorentin, P., Bailer-Jones, C. A. L., Norris, J. E., Rockosi, C. M., Yanny, B., Newberg, H. J., Covey, K. R., Zhang, H.-T. & Luo, A.-L. 2008a, *AJ*, 136, 2022

- Lee, Y. S., Beers, T. C., Sivarani, T., Johnson, J. A., An, D., Wilhelm, R., Allende Prieto, C., Koesterke, L., Re Fiorentin, P., Bailer-Jones, C. A. L., Norris, J. E., Yanny, B., Rockosi, C., Newberg, H. J., Cudworth, K. M. & Pan, K. 2008b, *AJ*, 136, 2050
- Lee, Y. S., Beers, T. C., Allende Prieto, C., Lai, D. K., Rockosi, C. M., Morrison, H. L., Johnson, J. A., An, D., Sivarani, T., & Yanny, B. 2011, *AJ*, 141, 90
- Lee, Y. S., Beers, T. C., An, D., Ivezić, Z., Just, A., Rockosi, C. M., Morrison, H. L., Johnson, J. A., Schönrich, R., Bird, J., Yanny, B., Harding, P., & Rocha-Pinto, H. J. 2011, arXiv, 1104.3114
- Loebman, S. R., Roskar, R., Debattista, V. P., Ivezić, Z., Quinn, T. R., & Wadsley, J. 2010, arXiv, 1009.5997
- Martin, P. & Roy, J.-R. 1994, *ApJ*, 424, 599
- Minchev, I. & Quillen, A. C. 2006, *MNRAS*, 368, 623
- Minchev, I. & Famaey, B. 2010, *ApJ*, 722, 112
- Minchev, I., Famaey, B., Combes, F., Di Matteo, P., Mouhcine, M., & Wozniak, H. 2011, *A&A*, 527, 147
- Minchev, I., Famaey, B., Quillen, A. C., & Dehnen, W. 2011, arXiv, 1111.0195
- Morrison, H. L., Norris, J., Mateo, M., Harding, P., Olszewski, E. W., Sheckman, S. A., Dohm-Palmer, R. C., Helmi, A., & Freeman, K. C. 2003, *AJ*, 125, 2502
- Mould, J. 1982, *ARA&A*, 20, 91
- Mould, J. 1996, *PASP*, 108, 35
- Nordström, B., Mayor, M., Andersen, J., Holmberg, J., Pont, F., Jørgensen, B. R., Olsen, E. H., Udry, S. & Mowlavi, N. 2004, *A&A*, 418, 989
- Norris, J. E. & Ryan, S. G. 1991, *ApJ*, 380, 403
- Padmanabhan, N., et al. 2008, *ApJ*, 674, 1217
- Pagel, B. E. J. & Patchett, B. E. 1975, *MNRAS*, 172, 13
- Pagel, B. E. J. 1997, Cambridge University Press
- Pier, J. R., Munn, J. A., Hindsley, R. B., Hennessy, G. S., Kent, S. M., Lupton, R. H., & Ivezić, Ž. 2003, *AJ*, 125, 1559
- Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2004, *ApJ*, 612, 168-190

- Prochaska, J. X., Naumov, S. O., Carney, B. W., McWilliam, A., & Wolfe, A. M. 2000, *AJ*, 120, 2513
- Quillen, A. C., Minchev, I., Bland-Hawthorn, J., & Haywood, M. 2009, *MNRAS*, 397, 1599
- Rana, N. C. & Basu, S. 1990, *Ap&SS*, 168, 317-330
- Randich, S., Sestito, P., Primas, F., Pallavicini, R., & Pasquini, L. 2006, *A&A*, 450, 557-567
- Reddy, B. E., Lambert, D. L., & Allende Prieto, C. 2006, *MNRAS*, 367, 1329
- Robin, A. C., Reyl  , C., Derri  re, S., & Picaud, S. 2003, *A&A*, 409, 523
- Rocha-Pinto, H. J. & Maciel, W. J. 1996, *MNRAS*, 279, 447
- Rocha-Pinto, H. J. & Maciel, W. J. 1997, *MNRAS*, 289, 882
- Rocha-Pinto, H. J. & Maciel, W. J. 1998, *A&A*, 339, 791-801
- Rocha-Pinto, H. J., Maciel, W. J., Scalo, J., & Flynn, C. 2000, *A&A*, 358, 850-868
- Romano, D., Chiappini, C., Matteucci, F., & Tosi, M. 2005, *A&A*, 430, 491
- Ro  kar, R., Debattista, V. P., Quinn, T. R., Stinson, G. S., Wadsley, J. 2008, *ApJ*, L79–L82
- Ryan, S. G. & Norris, J. E. 1991, *AJ*, 101, 1865
- Salpeter, E. E. 1955, *ApJ*, 121, 161
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525
- Schlesinger, K. J., Johnson, J. A., Lee, Y. S., Masseron, T., Yanny, B., Rockosi, C. M., Gaudi, B. S., & Beers, T. C. 2010, *ApJ*, 719, 996
- Schmidt, M. 1963, *ApJ*, 137, 758
- Sch  nrich, R. & Binney, J. 2009, *MNRAS*, 396, 203
- Sch  nrich, R. & Binney, J. 2009, *MNRAS*, 399, 1145
- Sellwood, J. A. & Binney, J. J. 2002, *MNRAS*, 336, 785
- Smith, J. A., Tucker, D. L., Kent, S. M., et al. 2002, *AJ*, 123, 2121
- Smolinski, J. P., Lee, Y. S., Beers, T. C., An, D., Bickerton, S. J., Johnson, J. A., Loomis, C. P., Rockosi, C. M., Sivarani, T., & Yanny, B. 2011, *AJ*, 141, 89
- Sommer-Larsen, J. 1991, *MNRAS*, 249, 368
- Soubiran, C., Bienayn  , O., & Siebert, A. 2003, *A&A*, 398, 141

- Truran, J. W. & Cameron, A. G. W. 1971, *Ap&SS*, 14, 179
- Tucker, D., Kent, S., Richmond, M. W., et al. 2006, *Astronomische Nachrichten*, 327, 821
- Tumlinson, J. 2006, *ApJ*, 641, 1
- Tumlinson, J. 2010, *ApJ*, 708, 1398
- van den Bergh, S. 1962, *AJ*, 67, 486
- VandenBerg, D. A. & Clem, J. L. 2003, *AJ*, 126, 778
- Wyse, R. F. G. & Gilmore, G. 1995, *AJ*, 110, 2771
- Yanny, B., Rockosi, C., Newberg, H. J., Knapp, G. R. et al. for the SDSS-II SEGUE collaboration 2009, *AJ*, 137, 4377
- Yoachim, P. & Dalcanton, J. J. 2008, *ApJ*, 682, 1004
- Yoachim, P. & Dalcanton, J. J. 2008, *ApJ*, 683, 707
- York, D. G., Adelman, J., Anderson, J. E., et al. 2000, *AJ*, 120, 1579
- Yoshii, Y. 1982, *PASJ*, 34, 365
- Yoshii, Y., Ishida, K., & Stobie, R. S. 1987, *AJ*, 93, 323



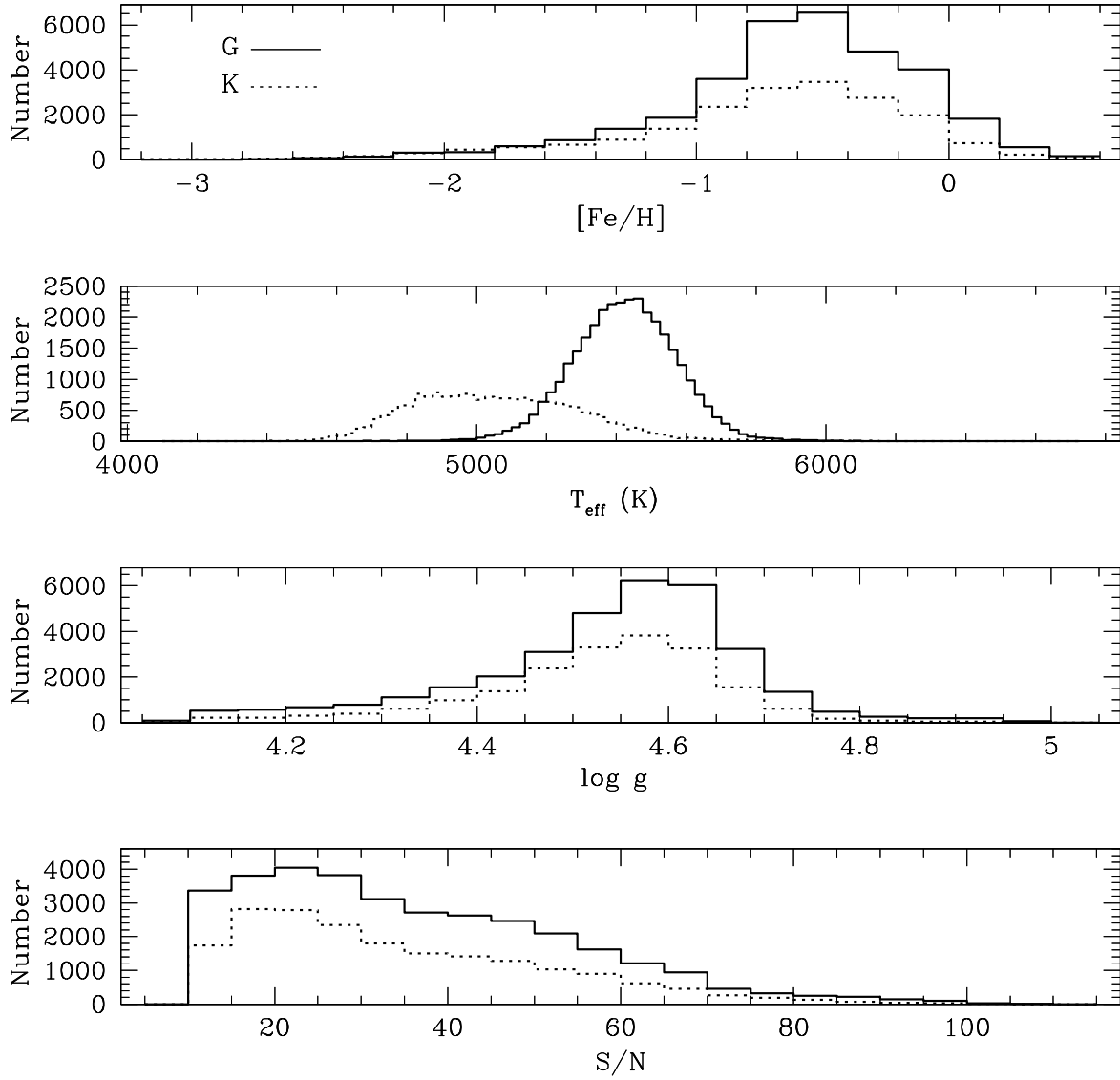


Fig. 1.— The atmospheric parameters of our sample of around 33,330 G and 19,600 K dwarfs with appropriate  $S/N$  and surface gravity. The solid line represents the G dwarfs, and the dotted line the K dwarfs. All of these stars have  $\log g \geq 4.1$ ,  $S/N \geq 10$  per pixel, where each pixel is  $\approx 1\text{\AA}$ , and a measured temperature and metallicity.

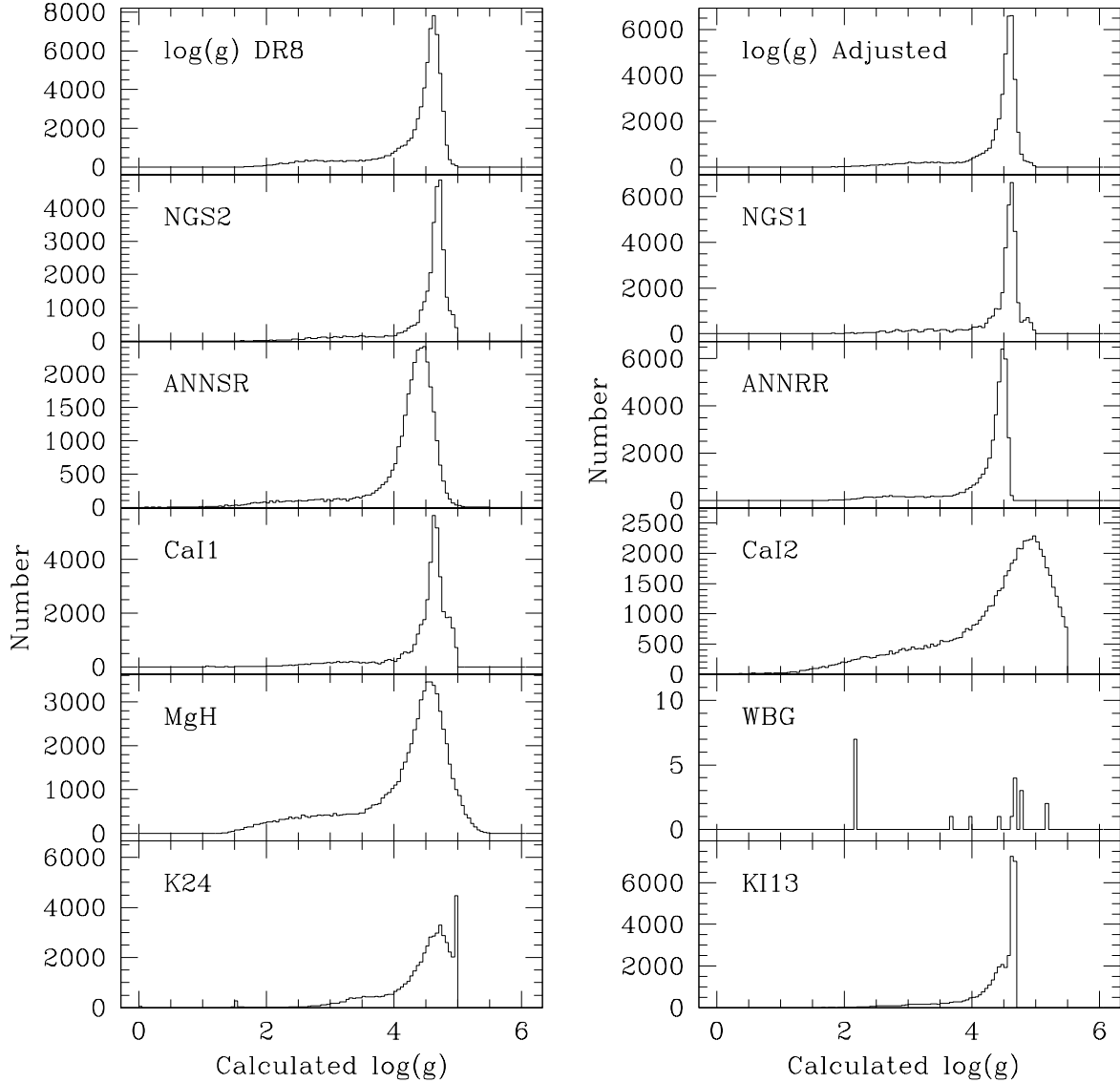


Fig. 2.— The surface gravities calculated using different methods in the SSPP for our sample of G and K dwarfs (see Lee et al. 2008a,b for a description of methods). The original adopted  $\log g$  distribution is in the top left. All of the distributions have a tail extending to  $\log g$  values indicative of giants. However, this tail is significantly more pronounced for the CaI2 and MgH methods. Additionally, the width of the peaks for these two methods are larger than that of the others, making their estimate of  $\log g$  generally more uncertain. The WBG method is, in general, unable to calculate a surface gravity for our targets. When the CaI2, MgH, and WBG techniques are removed, the low  $\log g$  tail is diminished, and the peak of the distribution is narrower. This corrected  $\log g$  is shown at the top right.

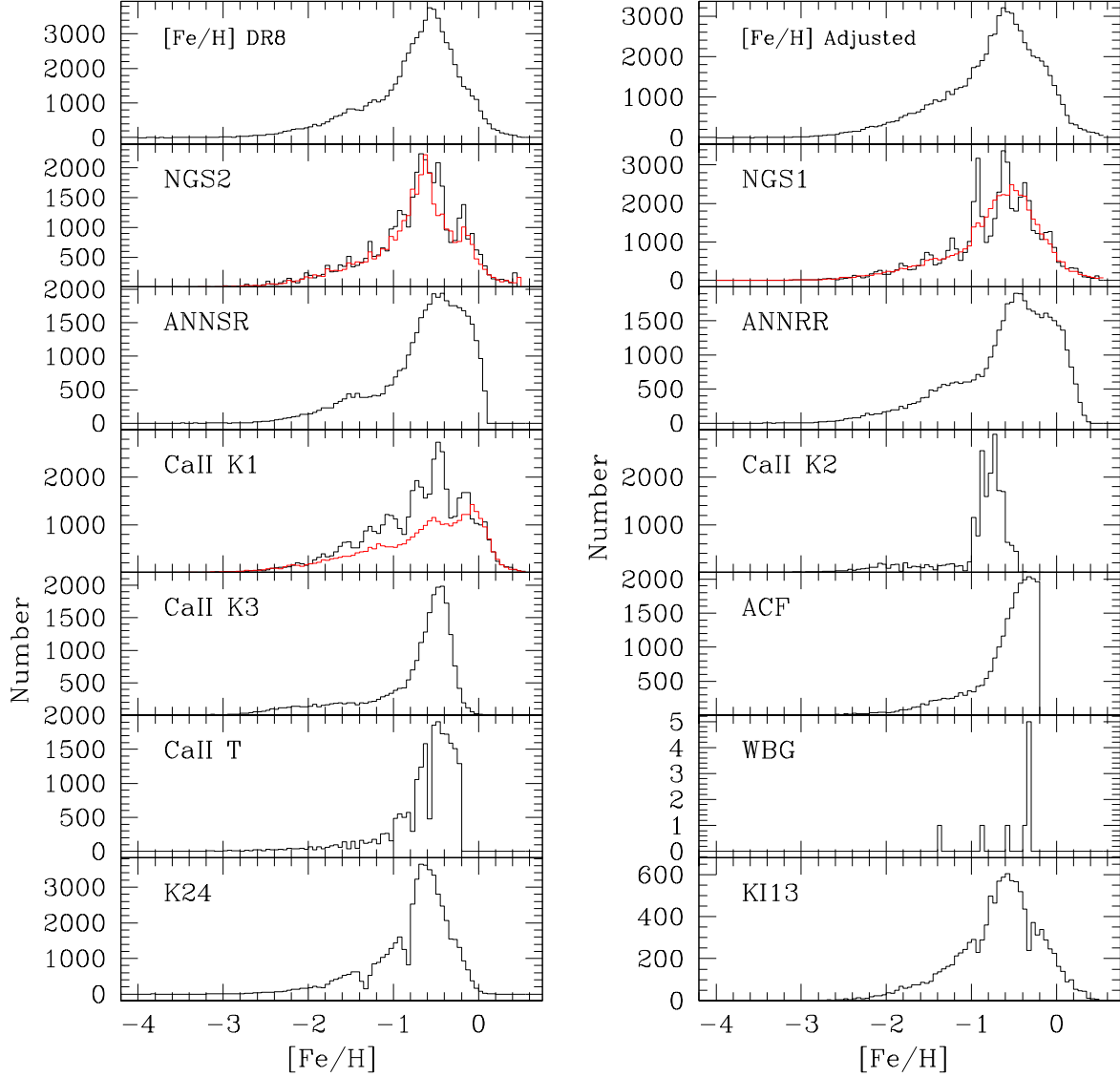


Fig. 3.— The metallicities calculated using different methods in the SSPP for our G- and K-dwarf sample. The original adopted  $[\text{Fe}/\text{H}]$  value is on the top left, with the adjusted distribution on the top right. For the different methods used in our optimized version of the SSPP, we plot the original distribution for the sample in black and the modified version in red. Note that for many methods, such as NGS1 and CaIIK1, the modified distribution is much smoother. We have also eliminated a number of methods as they are either not applicable for our sample or do not cover the appropriate metallicity range.

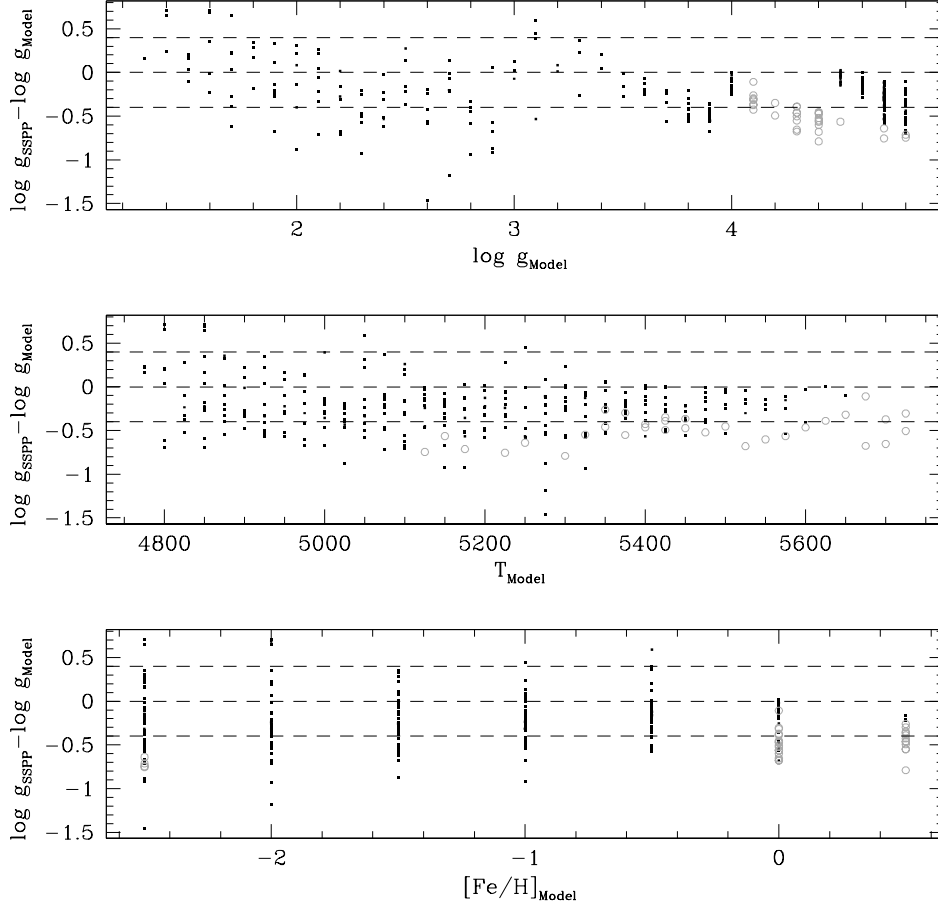


Fig. 4.— A comparison of the surface gravity values for the grid of synthetic spectra of dwarfs and subgiants to those determined by the SSPP. These synthetic spectra were degraded to be at a  $S/N$  of 25, where the expected SSPP uncertainty in  $\log g$  is  $\pm 0.40$  dex. The top panel shows the difference between the model and SSPP-calculated surface gravities with respect to that of the model. The gray open circles show the grid points where modeled stars with dwarf surface gravities have SSPP  $\log g$  of less than 4.1. The dashed lines show a change in  $\log g$  of 0 and  $\pm 0.4$  dex. The SSPP tends to underestimate the surface gravity of these synthetic spectra. There is some structure in  $\Delta \log g$  at the high  $\log g$  end; this is likely due to the continuum removal processes in the SSPP and is being examined for the SEGUE DR9 public data release. The middle figure shows the change in surface gravity with respect to model effective temperature. Dwarfs misidentified as subgiants tend to be at hotter temperatures. Finally, the bottom panel shows the distribution of  $\Delta \log g$  with respect to model  $[\text{Fe}/\text{H}]$ . Misidentified dwarfs tend to be the most metal-rich stars, although there are a few occurrences at the metal-poor end, where weak lines make it difficult to measure atmospheric parameters. The most metal-rich stars tend to have surface gravities close to the cutoff; even small underestimates can force them from the sample.

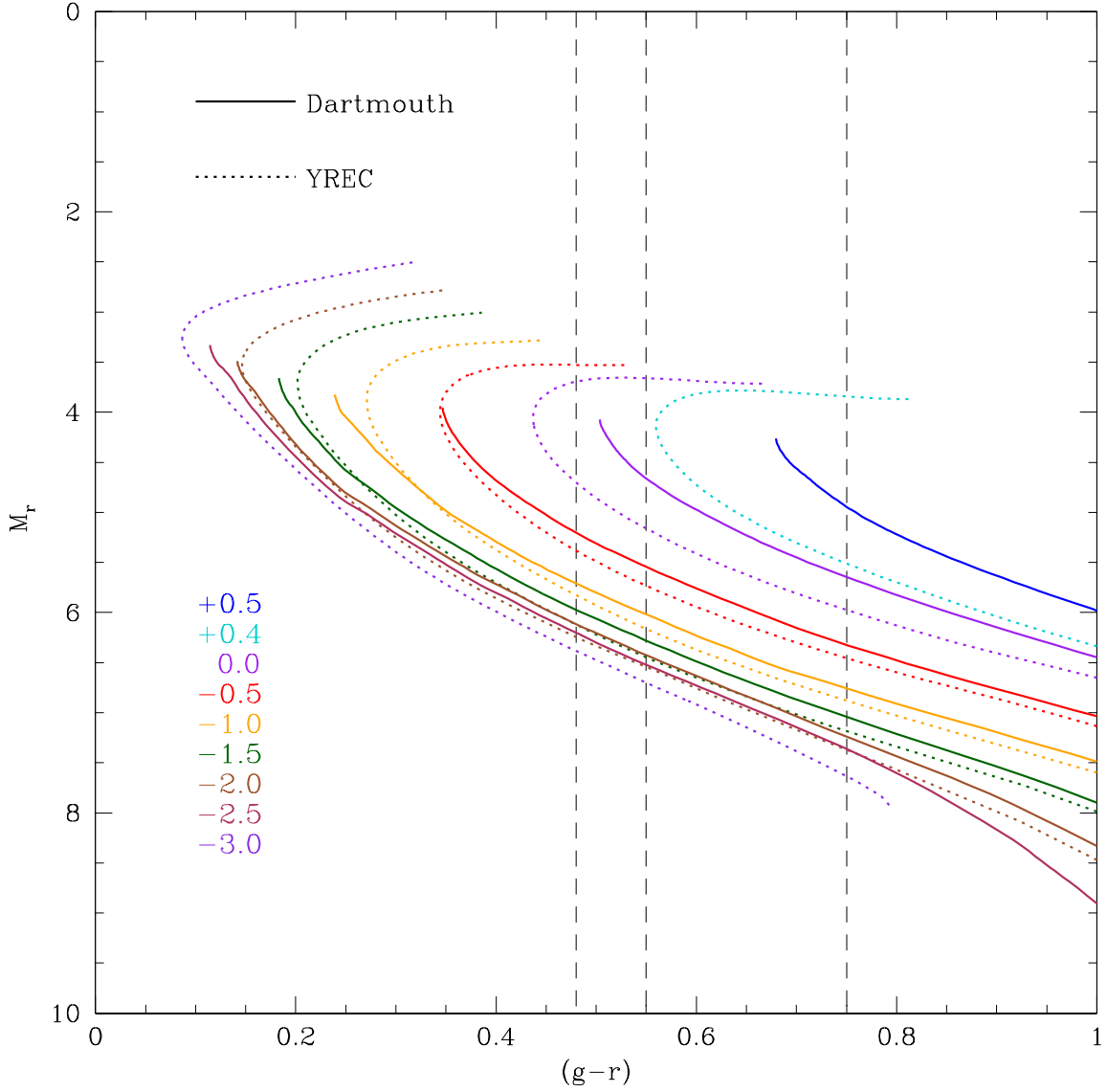


Fig. 5.— Comparison of the Dartmouth (solid) and YREC (dotted) isochrone sets for a range of metallicities at an age of 10 Gyr. Each color is associated with a specific  $[\text{Fe}/\text{H}]$ , as listed in the bottom left corner. The vertical dashed lines show the  $(g-r)$  color range for SEGUE G and K dwarfs. The Dartmouth isochrones are calculated until the main-sequence turn off, whereas the YREC isochrones extend up the subgiant branch.

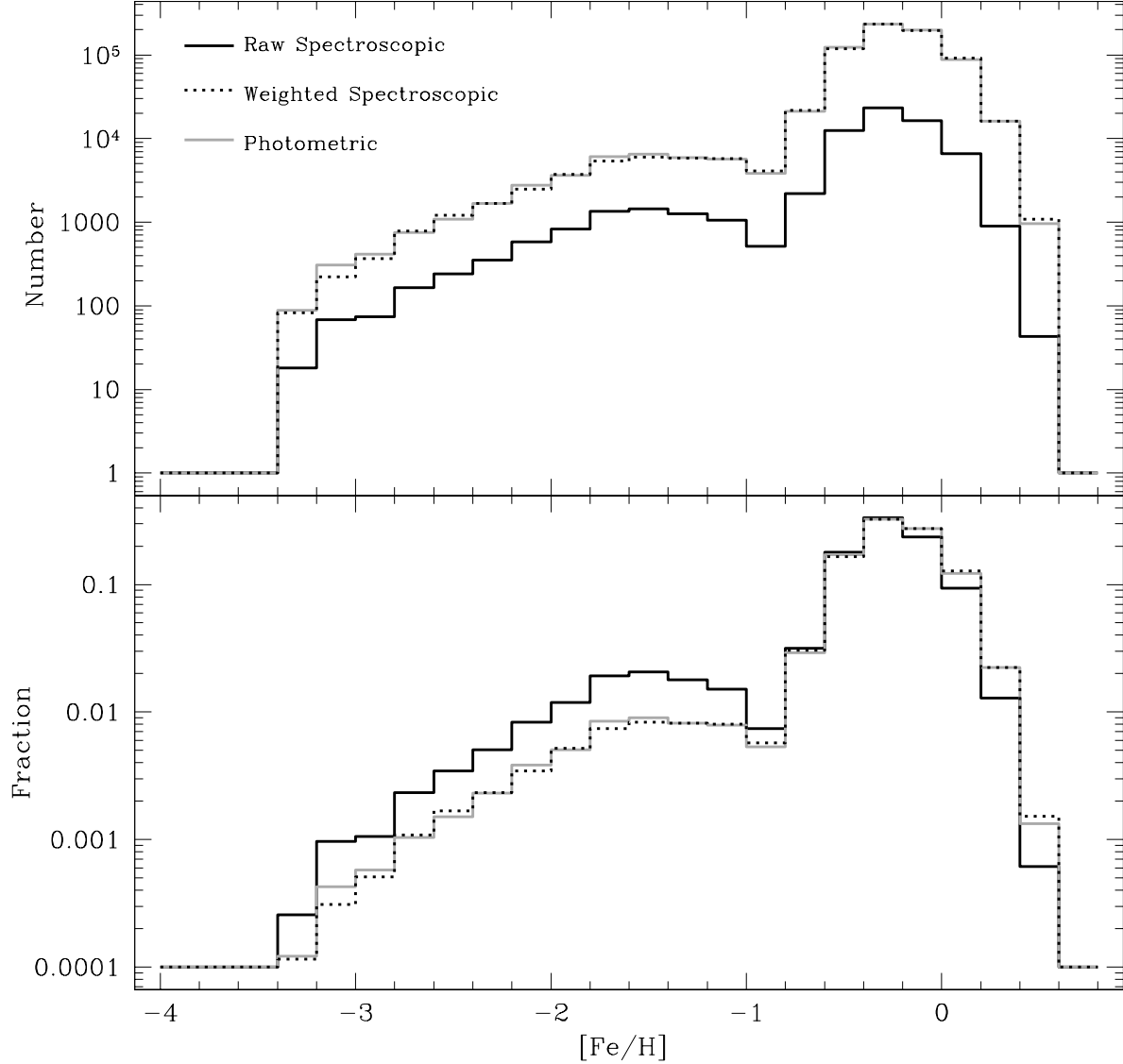


Fig. 6.— A test of the target-type and  $r$ -magnitude weighting system on the TRILEGAL Galaxy model. The solid black line represents the distribution of a randomly selected subsample of G and K dwarfs representing the SEGUE spectroscopic sample, which we refer to as the “raw spectroscopic.” The gray line is the distribution of every modeled star that meets the G- and K-dwarf photometric criteria. Finally, the dashed line is the distribution of the spectroscopic sample once we have weighted it in  $r$ -magnitude and target type. The top figure shows the numerical distribution of the three samples; the good match between the weighted spectroscopic and photometric distributions indicates that our technique accurately corrects for SEGUE target selection biases. The bottom figure shows the fractional distribution of the three samples. The “raw” spectroscopic sample is biased towards metal-poor stars, but our weighting scheme corrects for this.

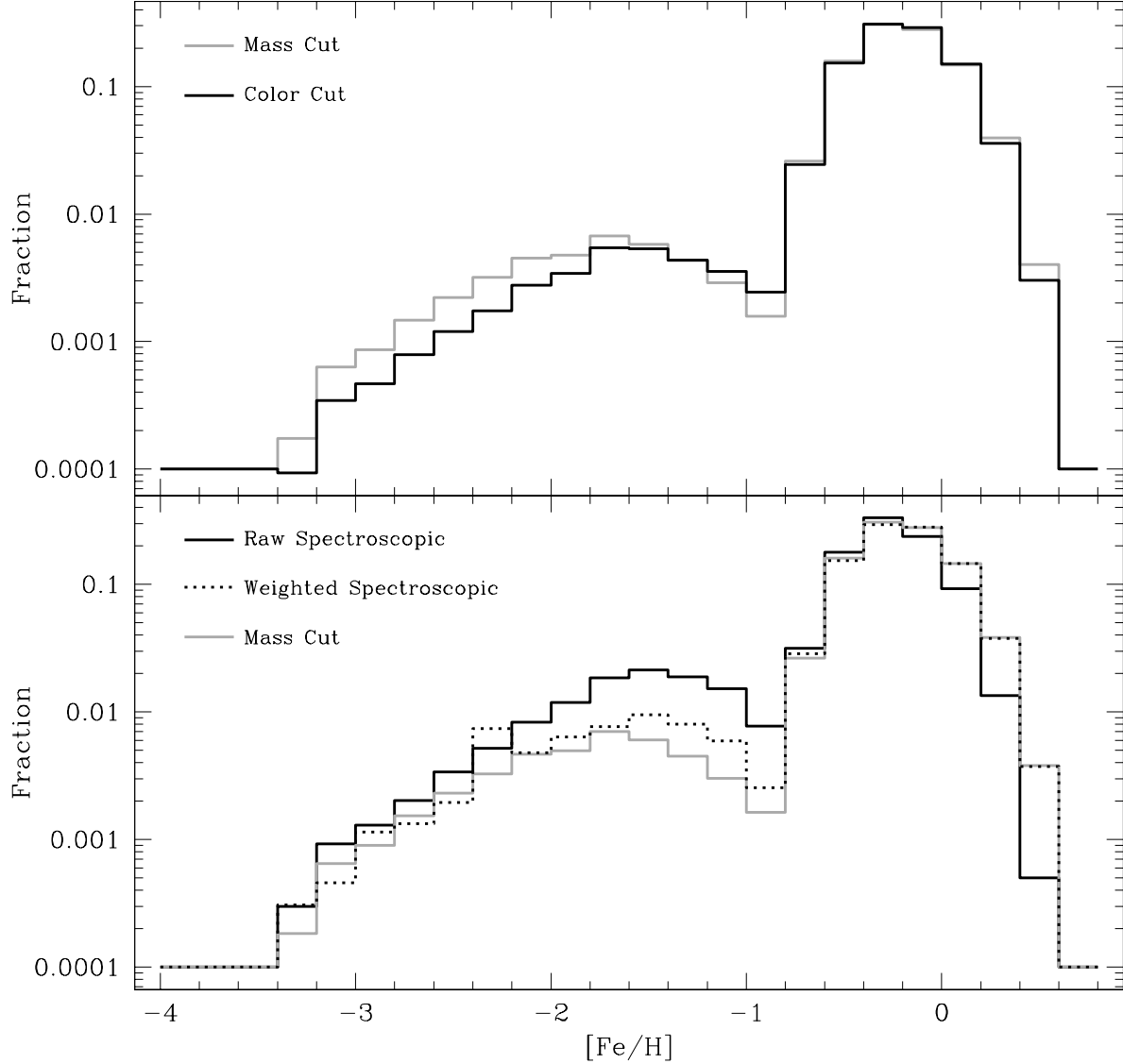


Fig. 7.— A test of the mass-function weights on the SEGUE lines of sight modeled with TRILEGAL. The top figure compares the effect of a color cut on the metallicity distribution to a mass cut. The color cut extracts all stars within the magnitude and  $(g - r)$  range of the SEGUE G and K dwarfs, shown in black. The mass cut selects all stars within the magnitude range with masses between  $0.5$  and  $0.6 M_{\odot}$ , shown in gray. The two distributions are quite similar, although there are some discrepancies at the metal-poor end. The bottom row tests our weighting scheme. The gray distribution remains the same as in the top plot. The additional distributions represent a randomly chosen G/K dwarf subsample to represent SEGUE spectroscopy (black) and this distribution weighted in target type,  $r$ -magnitude, and mass function (dashed). The weighted distribution scales the raw spectroscopic down at the metal-poor end and boosts the metal-rich end, such that it simulates isolating a uniform portion of the mass function.

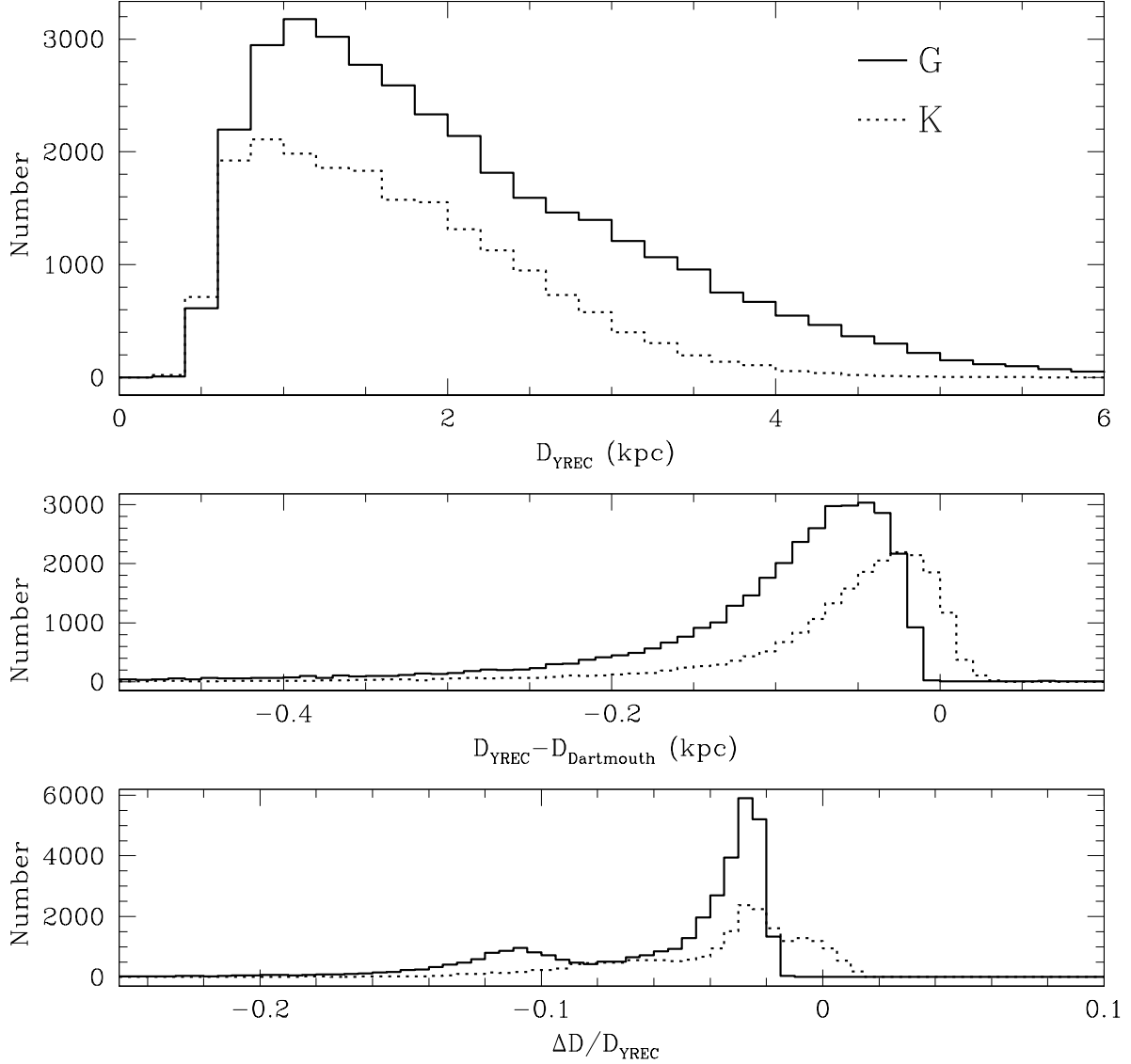


Fig. 8.— The top plot shows the distribution of G- (solid) and K-dwarf (dashed) distances, calculated by matching to YREC Isochrones. The K dwarfs tend to be closer in distance than the G dwarfs, which we expect as they are typically less luminous. The K dwarfs are peaked at a distance of around 0.95 kpc; the G dwarfs peak around 1.25 kpc. The volume-complete distance range for K dwarfs and G dwarfs ranges from 1.19 to 1.84 kpc and 1.59 to 2.29 kpc, respectively. The middle plot examines how the distances for the two spectral types change with different isochrones. The bottom plot presents the percent change in distance with the isochrone change. For both G and K dwarfs, the distances calculated using Dartmouth isochrones are larger than those using YREC isochrones by around 5% (see Appendix A.2.3). There is a noticeable second peak in the G-dwarf distribution; this represents the larger uncertainties at the metal-rich end, where the two isochrone sets are more discrepant (see Figure 5).



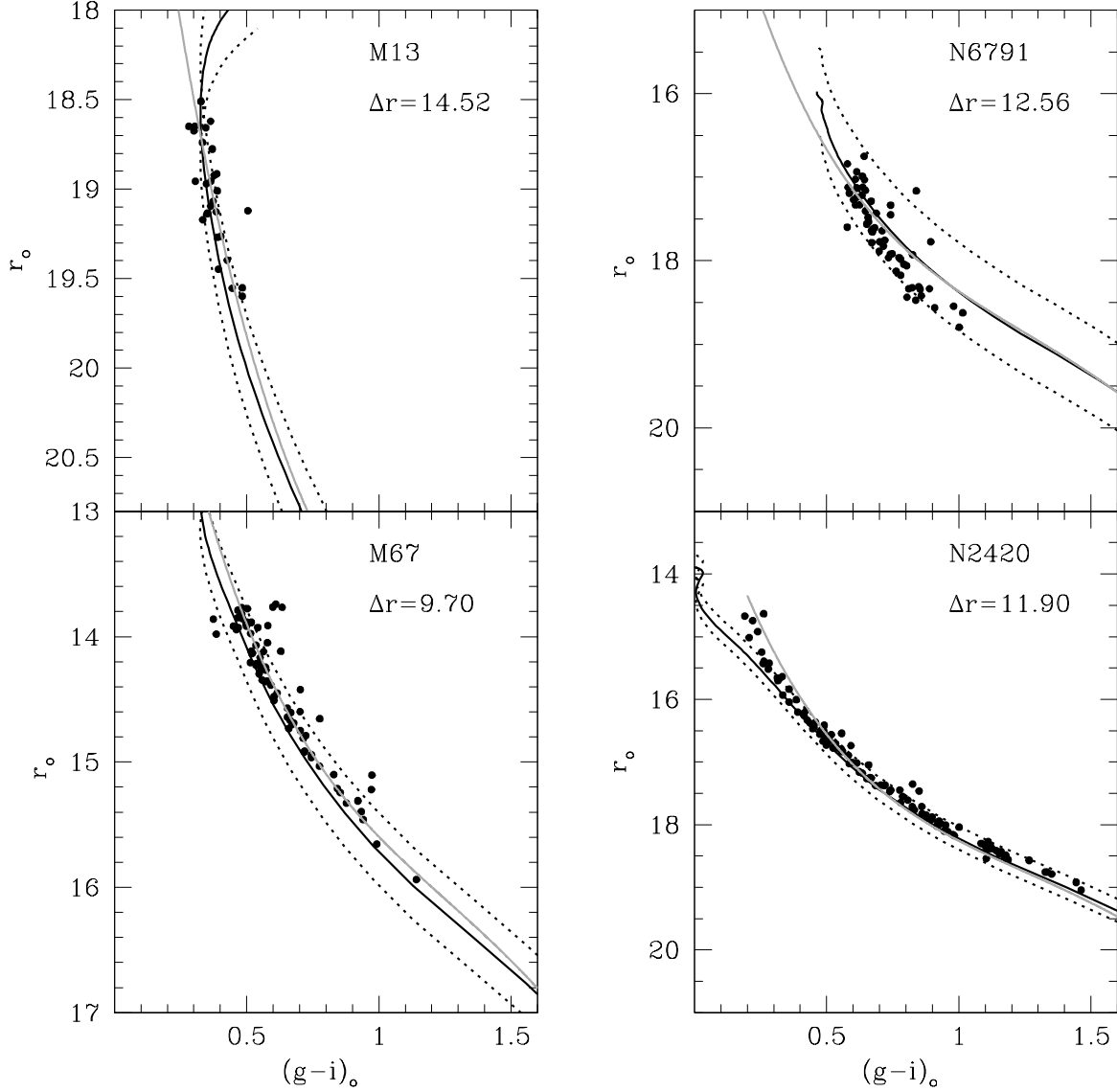


Fig. 9.— Dwarf targets in various open and globular clusters compared to shifted YREC isochrones of comparable age (listed in Table 2). For each cluster, we extract all targets with  $\log g \geq 4.1$  and calculate their distance using a set of different methods. We have shifted the isochrones according to the mean distance for each cluster from the YREC isochrone technique (in black). The short dashed lines shift the isochrone by the  $1\sigma$  dispersion of the distance measurements for each cluster. The gray lines show the photometric parallax relationship using the mean SSPP metallicity of the clusters (see § C). Each plot is labeled with the name of the cluster and the distance modulus used to shift the isochrones. The cluster distances determined using all of our methods are listed in Table 2.

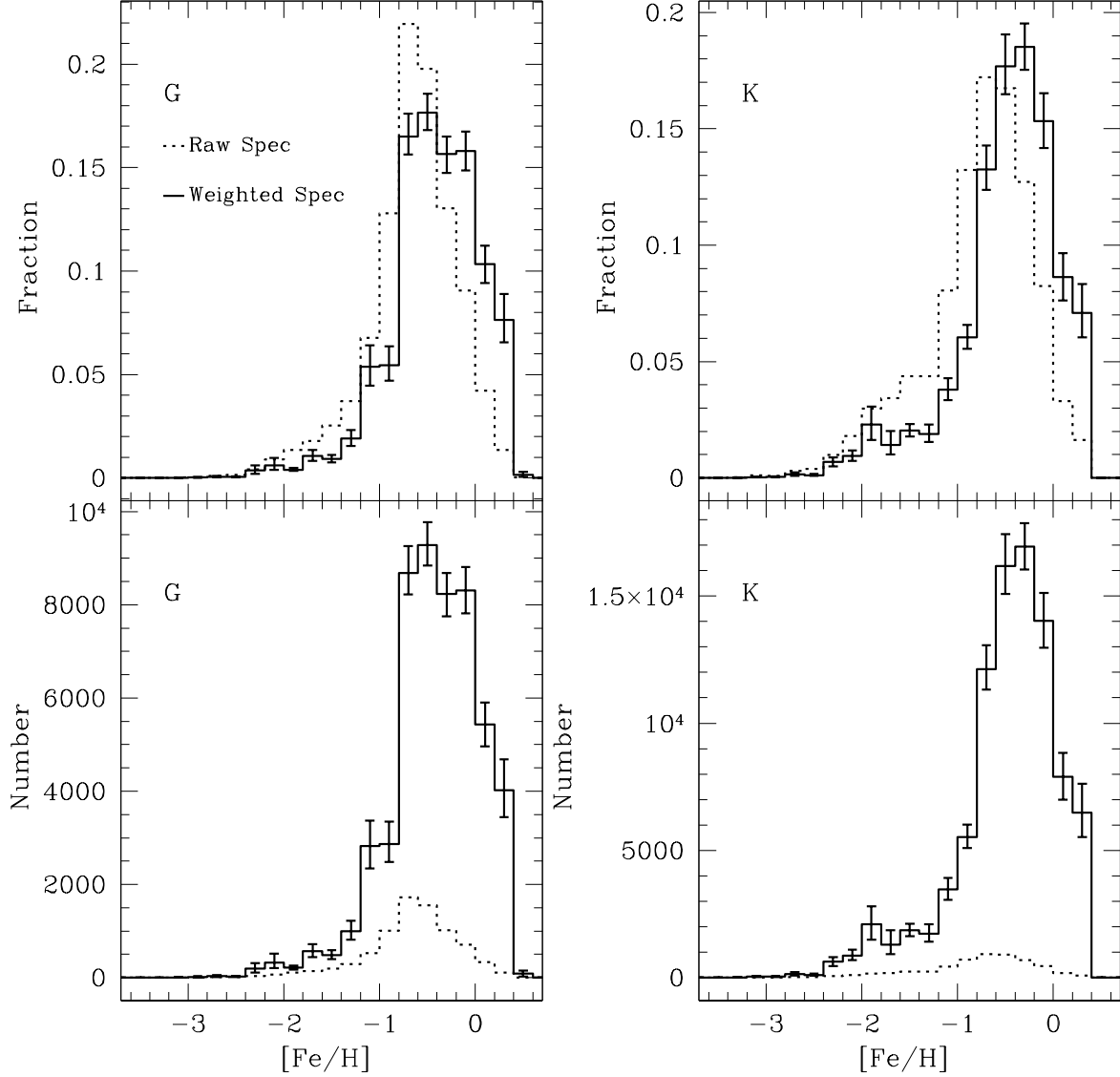


Fig. 10.— The raw and weighted MDF for the G (left) and K (right) dwarfs. The raw spectroscopic sample is the dashed line. The sample adjusted for target-type,  $r$ -magnitude, and mass-function weights is the solid line. The error bars on the solid line reflect the error in each bin based on our bootstrap error analysis (§ 5.1). Both samples are limited to their spectral type distance ranges, as described in § 4.5. Note that the corrections associated with the target selection scheme boost the metal-rich end of the distribution.

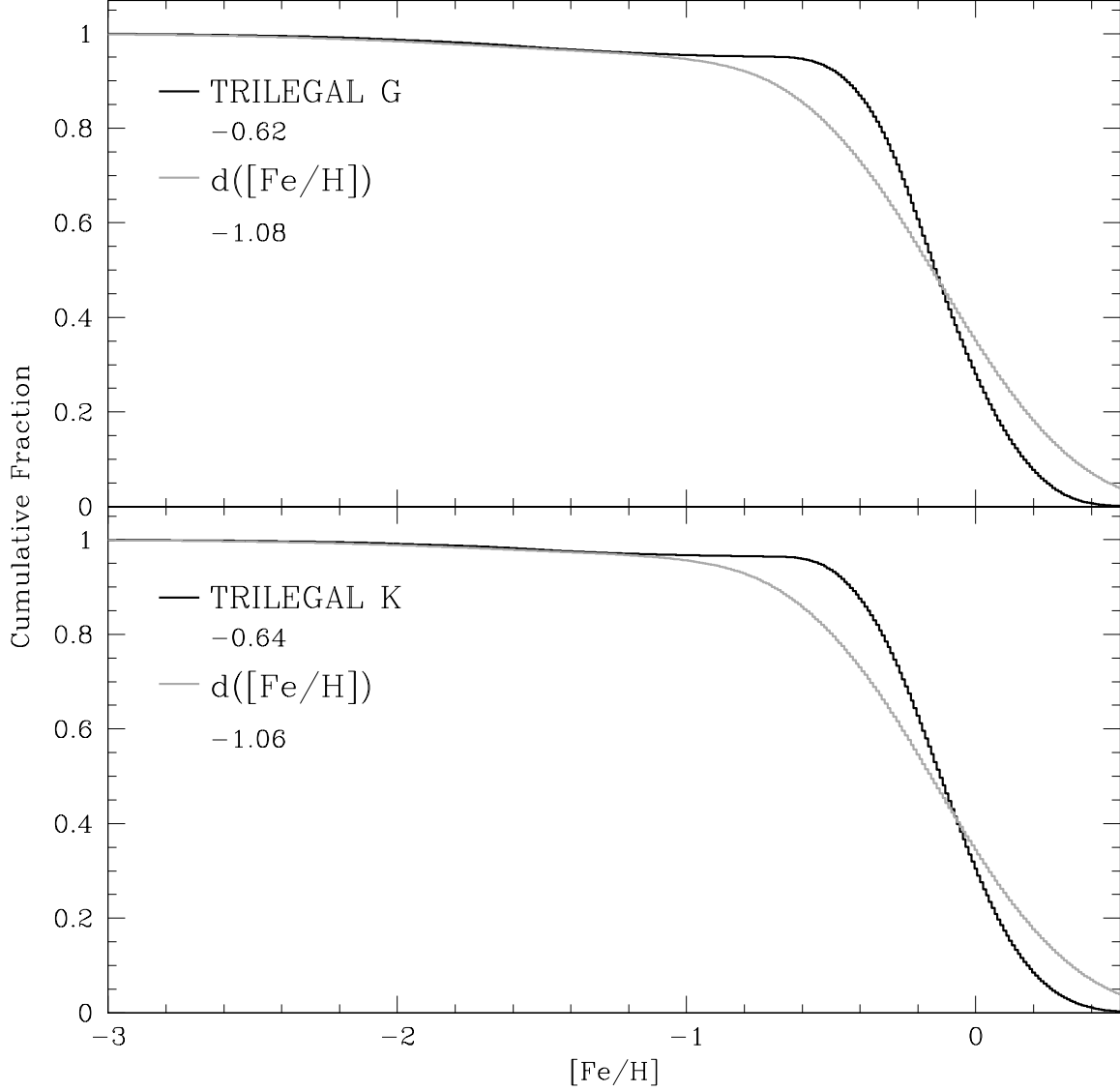


Fig. 11.— Comparison of the true cumulative metallicity distribution from the TRILEGAL model to a distribution which includes the correlated uncertainties in  $[\text{Fe}/\text{H}]$  and distance. We simulate the G (top, black) and K (bottom, black) dwarfs in SEGUE using a TRILEGAL model. Using a Monte-Carlo analysis, we factor in the uncertainties in  $[\text{Fe}/\text{H}]$  and the resulting change in distance. This broadens the metallicity distribution a significant amount, as indicated by the gray  $d([\text{Fe}/\text{H}])$  lines. We estimate the slopes of these distributions between a cumulative fraction of 0.25 and 0.75; they are listed on the figure. This change estimates the amount of broadening in our MDFs caused by errors in metallicity.

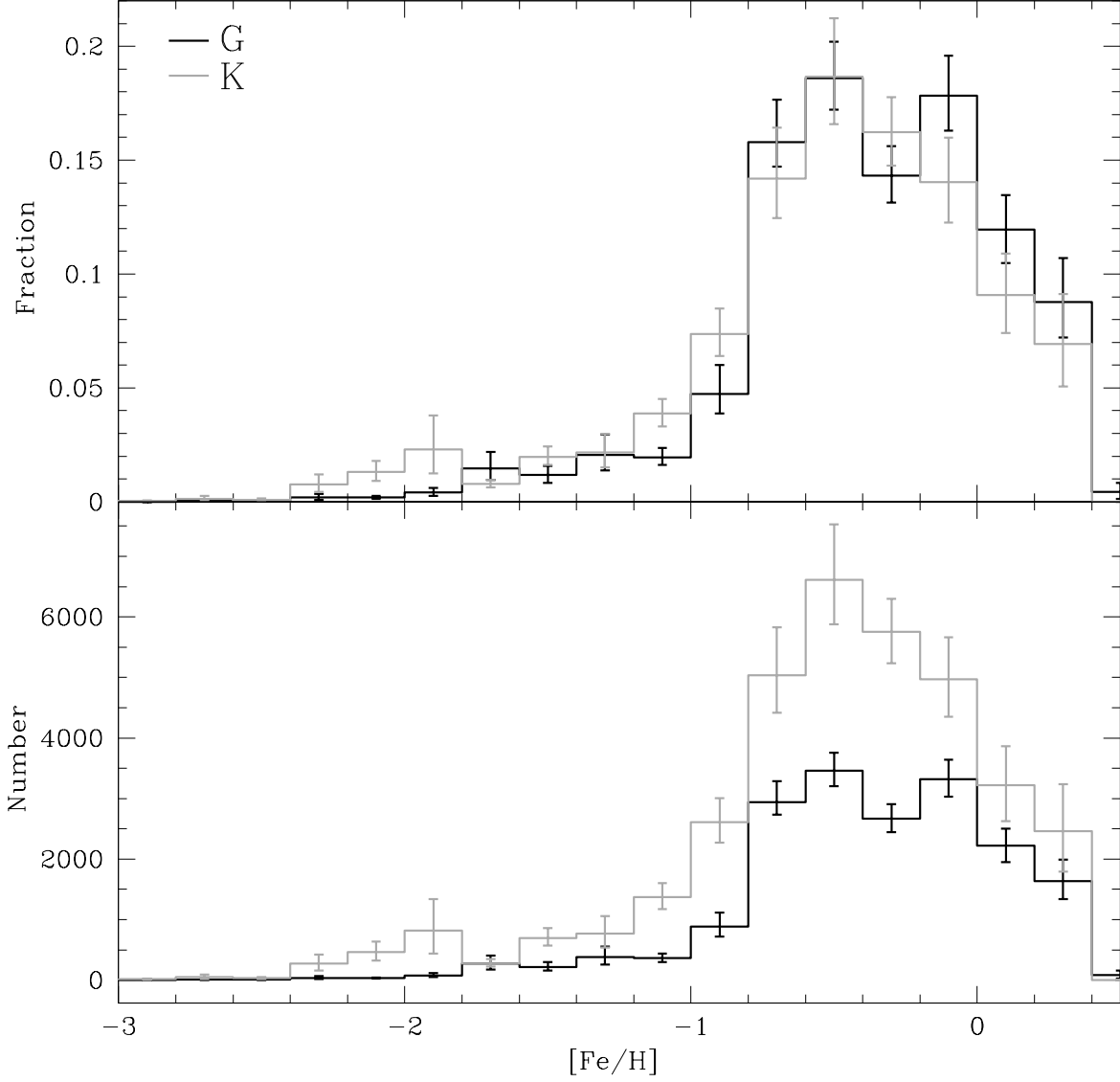


Fig. 12.— Comparison of the G- (black) and K-dwarf (gray) MDFs. Both samples are limited to distances between 1.59 and 1.84 kpc. The error bars are based upon our bootstrap analysis over 500 iterations. The two samples cover a similar metallicity range and peak at approximately the same value.

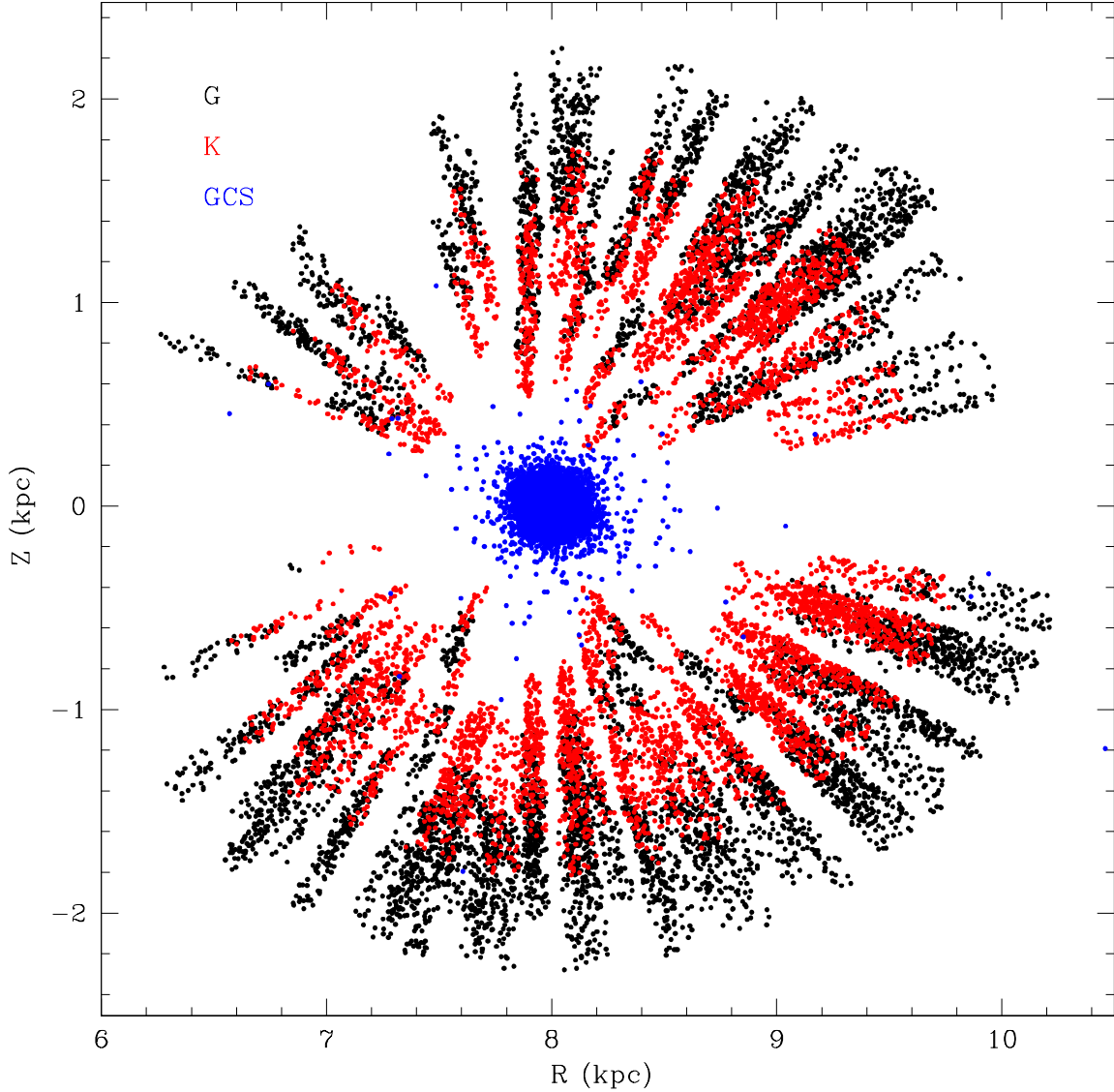


Fig. 13.— The spatial positions of our G (black) and K (red) dwarfs. The Geneva-Copenhagen Survey (GCS) sample of stars is shown in blue (Nordström et al. 2004; Haywood 2008; Casagrande et al. 2011). The G dwarfs are limited to distances between 1.59 and 2.29 kpc, whereas K dwarfs fall between 1.18 and 1.84 kpc, based on the magnitude limits of SEGUE. This reduces our stellar sample to 5,407 K- and 7,834 G-dwarfs. Our sample probes the disk both towards and away from the Galactic center and above and below the Galactic plane, with the line-of-sight structure of SEGUE clearly visible. The GCS sample is limited to the solar neighborhood, with distances typically less than 200 pc.

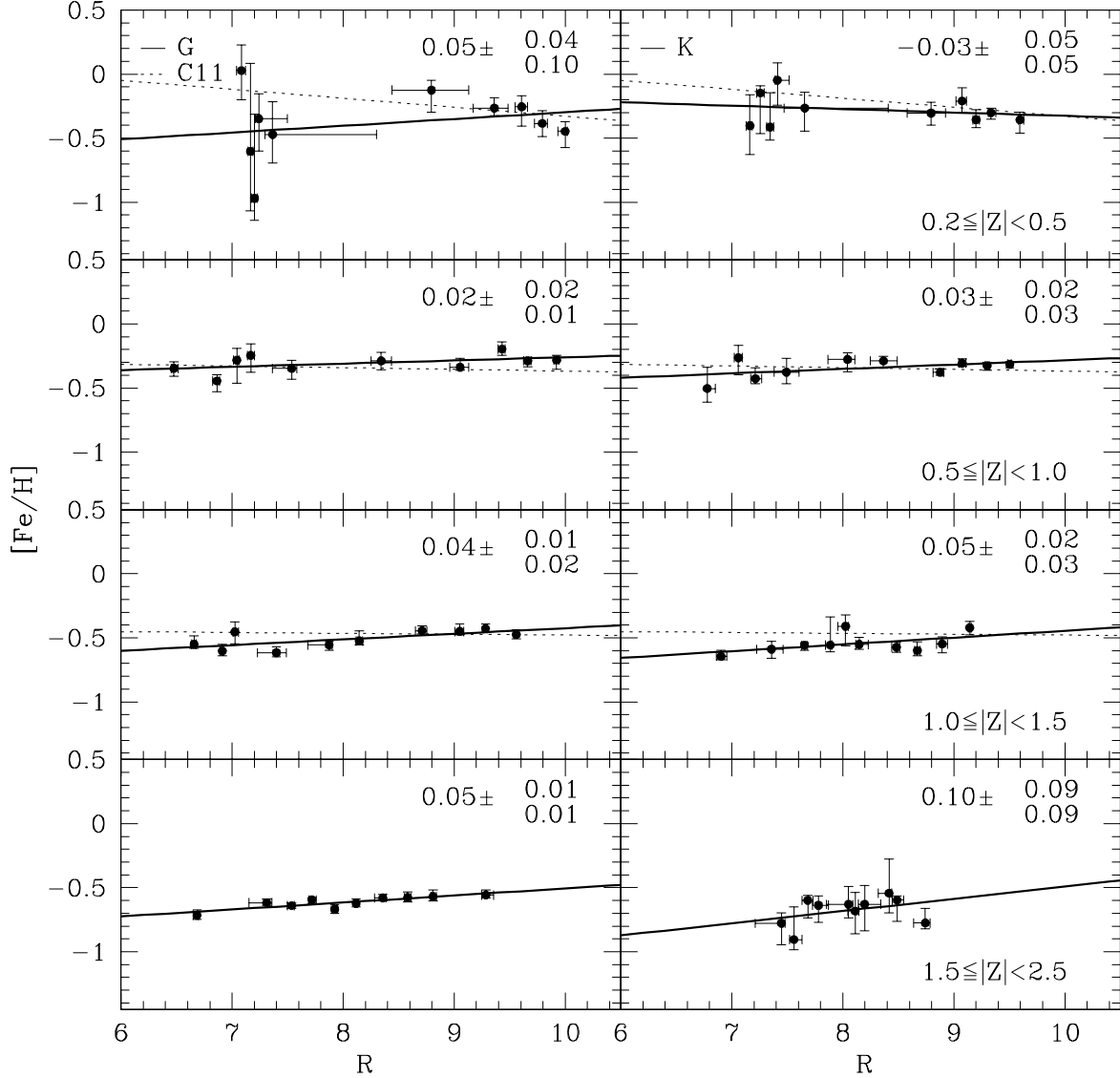


Fig. 14.— Determination of the radial metallicity gradient in different bins of  $|Z|$  of our G- (left) and K-dwarf (right) sample. The black points show the median  $R$  and  $[Fe/H]$  for 10 bins of equal weighted number. The uncertainties on each of these points are from a bootstrap analysis and reflect the standard deviation of the median points in  $R$  and  $[Fe/H]$ . The black line is the least squares linear fit to these median values; the slope and its uncertainties, also from our bootstrap analysis, are listed in the top right corner of each plot. Note that the correlated uncertainties in  $[Fe/H]$  and distance will create an artificial positive slope in the radial direction; we quantify this systematic bias in each radial bin using the TRILEGAL Galaxy model (see Table 4). The dotted lines up to  $|Z|$  of 1.5 kpc are the gradients from the Cheng et al. (2011) sample of MSTO stars on low-latitude SEGUE plates. Our results are consistent with those from Cheng et al. (2011) within the uncertainty. To avoid halo contamination, we have removed all stars with  $[Fe/H] \leq -1.4$ .

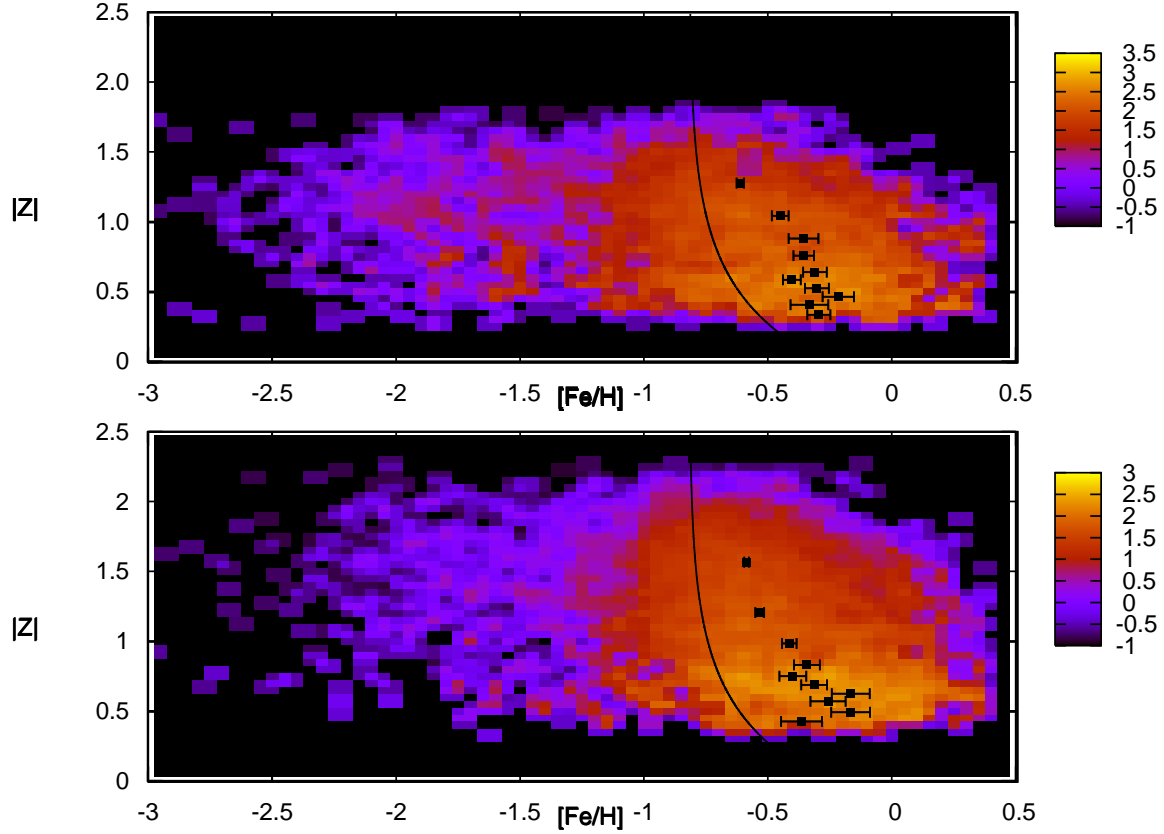


Fig. 15.— The distribution of G (bottom) and K dwarfs (top) in  $[\text{Fe}/\text{H}]$  with respect to  $|Z|$ . Stars are sorted into bins of  $[\text{Fe}/\text{H}]$  and  $|Z|$ . The number of stars in each bin is then adjusted using the target-type,  $r$ -magnitude, and mass-function weights. The logarithm of the weighted number of targets is indicated by color, as labeled on the right side. The black points indicate the median  $[\text{Fe}/\text{H}]$  and  $|Z|$  value for 10 bins of equal weighted number for all stars with  $[\text{Fe}/\text{H}] > -1.4$ , to avoid halo contamination. The error bars reflect the standard deviation of each median point over 100 bootstrap iterations. The black line is the analytic vertical metallicity gradient for the disk determined by Bond et al. (2010) using SDSS photometric metallicities.

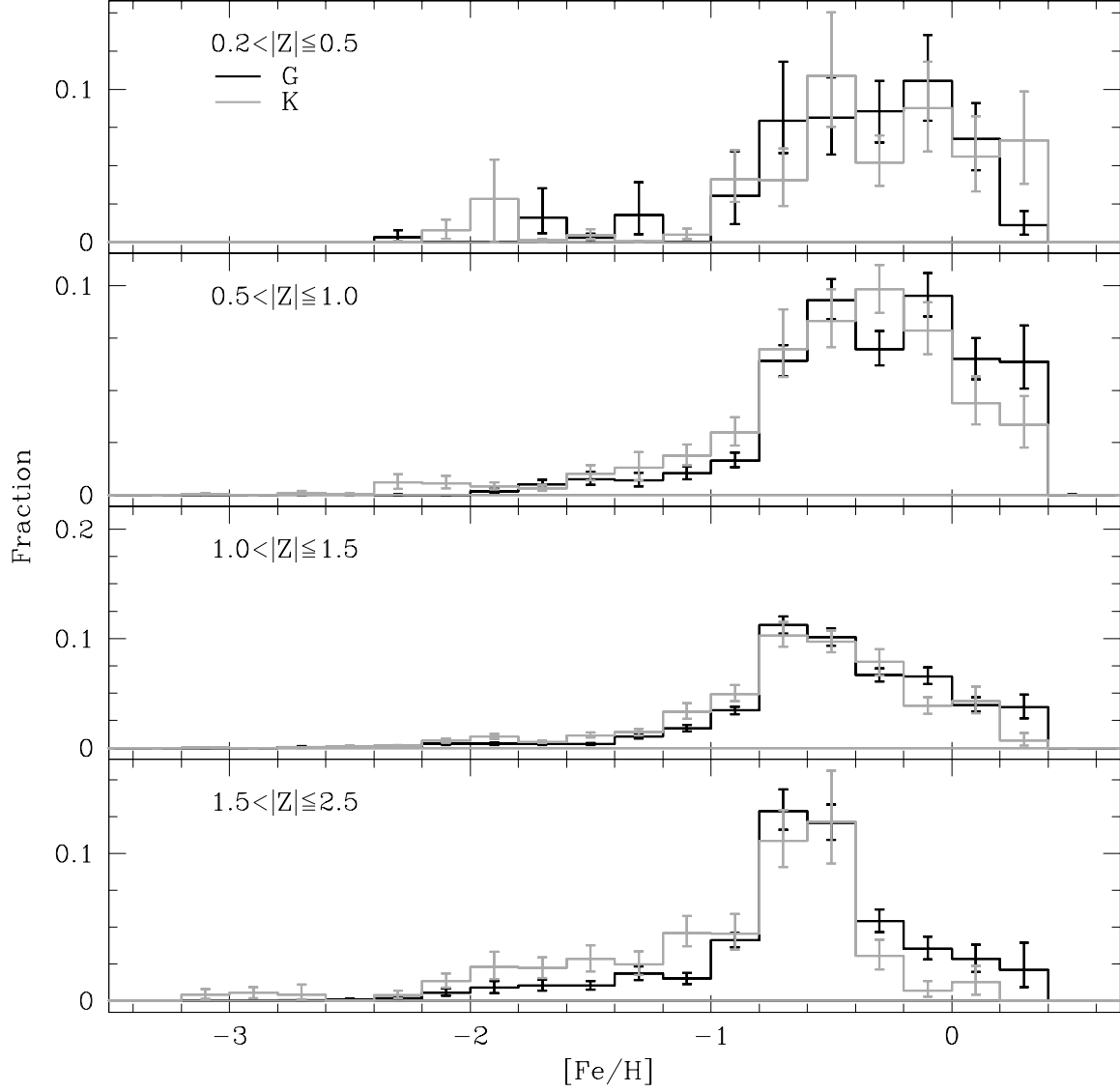


Fig. 16.— The volume-complete weighted MDF for the G (black) and K (gray) dwarfs at a range of  $|Z|$ , where  $|Z|$  is the current distance from the plane in kpc. The uncertainty in each bin was determined from our bootstrap analysis over 500 iterations. These distributions are listed in Table 7 and 8.



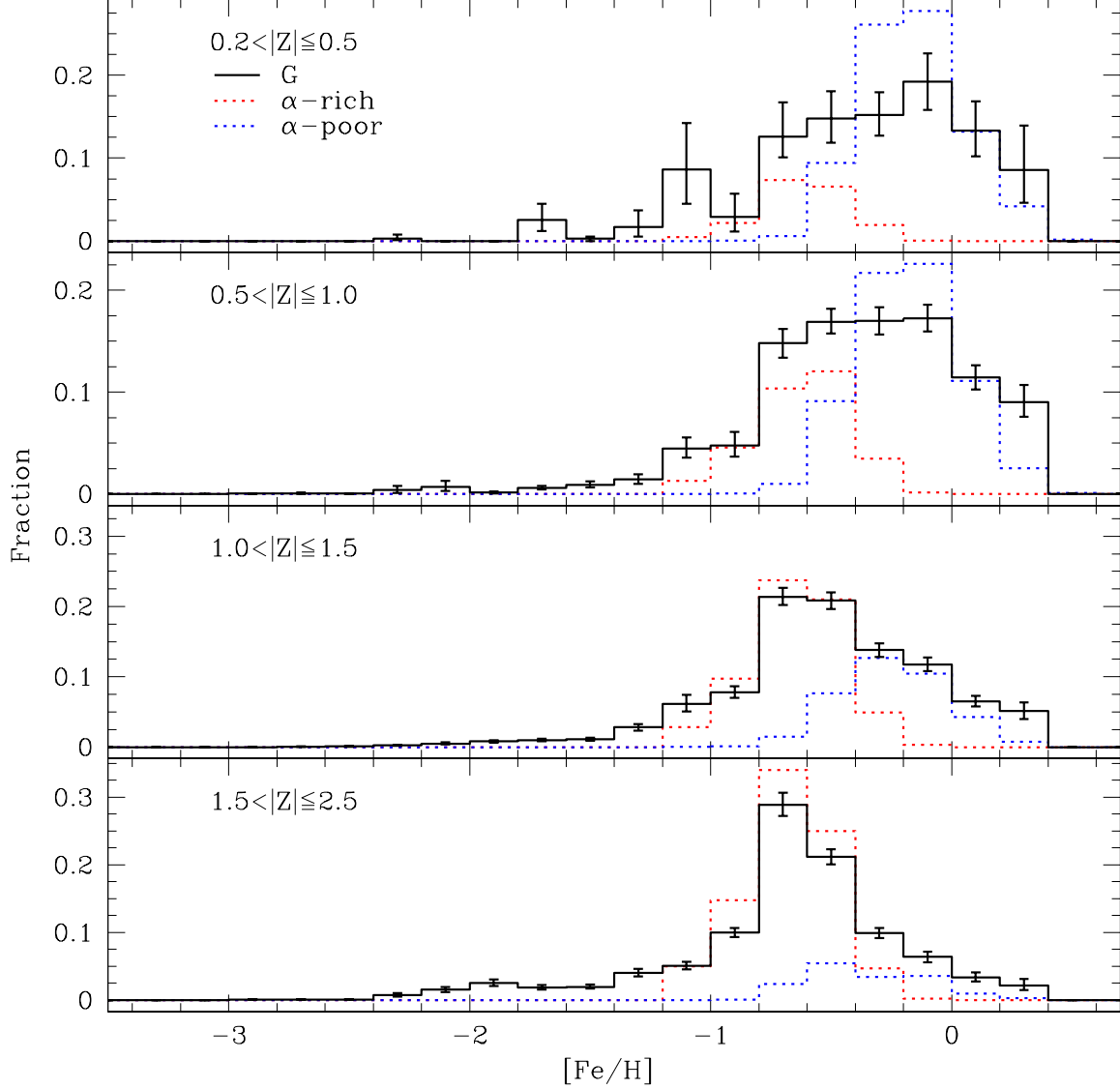


Fig. 17.— Comparison of the SEGUE G-dwarf MDF over the spectral type distance range with that of Lee et al. (2011b). Their work is based on the SEGUE G-dwarf sample and uses  $[\alpha/\text{Fe}]$  to discriminate between the thin and thick disk. Our SEGUE G dwarfs are plotted in black. The blue dotted line is the Lee et al. (2011b)  $\alpha$ -poor sample. The red dotted line is their  $\alpha$ -enhanced distribution, associated with the thick disk. In our distributions, the G-dwarf peak shifts from the  $\alpha$ -poor to match that of the  $\alpha$ -enhanced sample with increasing  $|Z|$ . Our observed vertical metallicity gradient reflects a change in disk population from thin- to thick-disk stars.

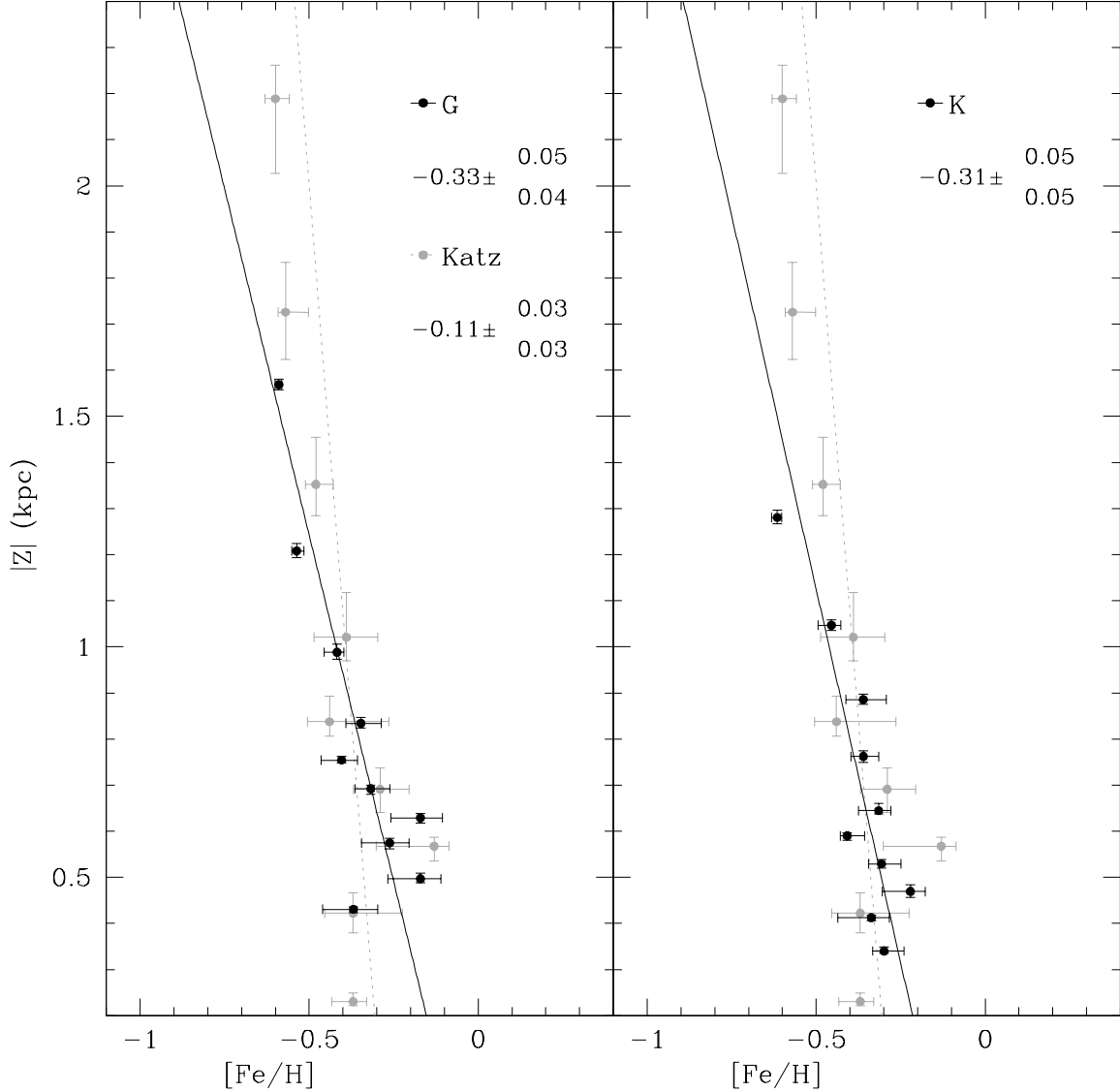


Fig. 18.— The gradient in  $|Z|$  with respect to  $[\text{Fe}/\text{H}]$ . G dwarfs are plotted on the left, K dwarfs on the right. We break the sample into 10 bins of equal weighted number. The black line is the linear least squares fit to these points, with the slope reported in the top right corner. The black points represent the median  $|Z|$  and  $[\text{Fe}/\text{H}]$  for each bin, and the error bars on each point reflect the standard deviation in the median values from a bootstrap analysis. The gray points show the behavior of the Katz et al. (2011) sample, analyzed in the same fashion; the size of our sample results in uncertainties much smaller than those from Katz et al. (2011). Using TRILEGAL simulated lines of sight, we estimate the effect of correlated  $[\text{Fe}/\text{H}]$  and distance uncertainties on the calculated gradients; they are listed in Table 9. The uncertainties will shift the calculated slopes to smaller values, implying that our vertical gradient over the disk is larger than  $-0.33$ . Note that all stars with  $[\text{Fe}/\text{H}] \leq -1.4$  have been removed from this sample to avoid halo contamination.

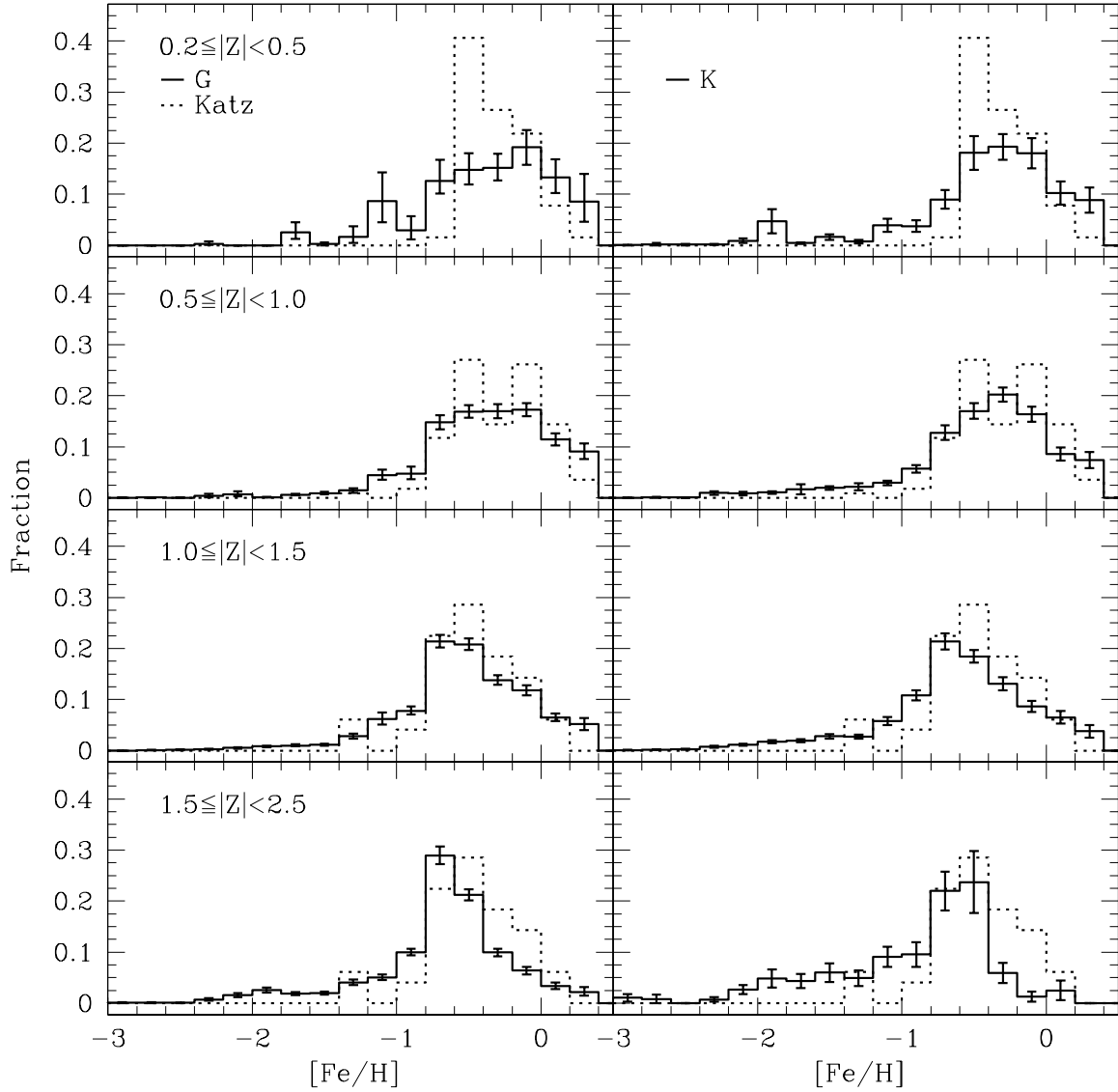


Fig. 19.— Comparison of the SEGUE G- (left) and K-dwarf (right) MDFs with the distribution of Katz et al. (2011). The SEGUE samples are represented by the solid line, they cover the spectral type distance ranges. The Katz et al. (2011) distributions are plotted as the dashed lines. The Katz et al. (2011) sample tends to be deficient at the metal-poor end.

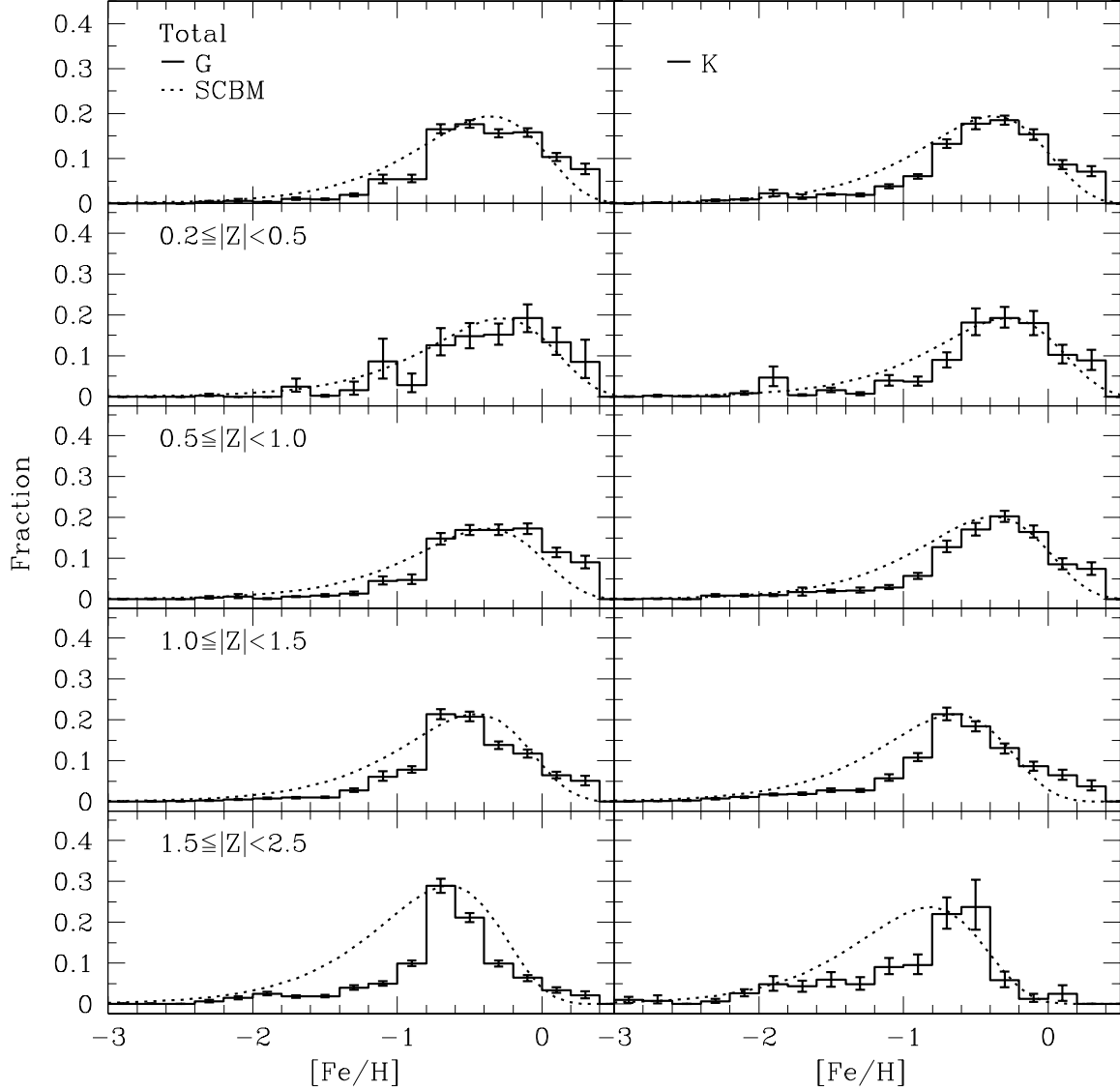


Fig. 20.— Comparison of the G- (left) and K-dwarf (right) sample in bins of  $|Z|$  with a simple closed box model (dotted line) assuming instantaneous recycling (Schmidt 1963). The total metallicity distribution for each spectral type over its associated distance range is shown in the top row. The size of the discrepancy between the observed distribution and the model at the metal-poor end is consistent for G and K dwarfs. The G- and K-dwarf problem is evident throughout the Milky Way disk.

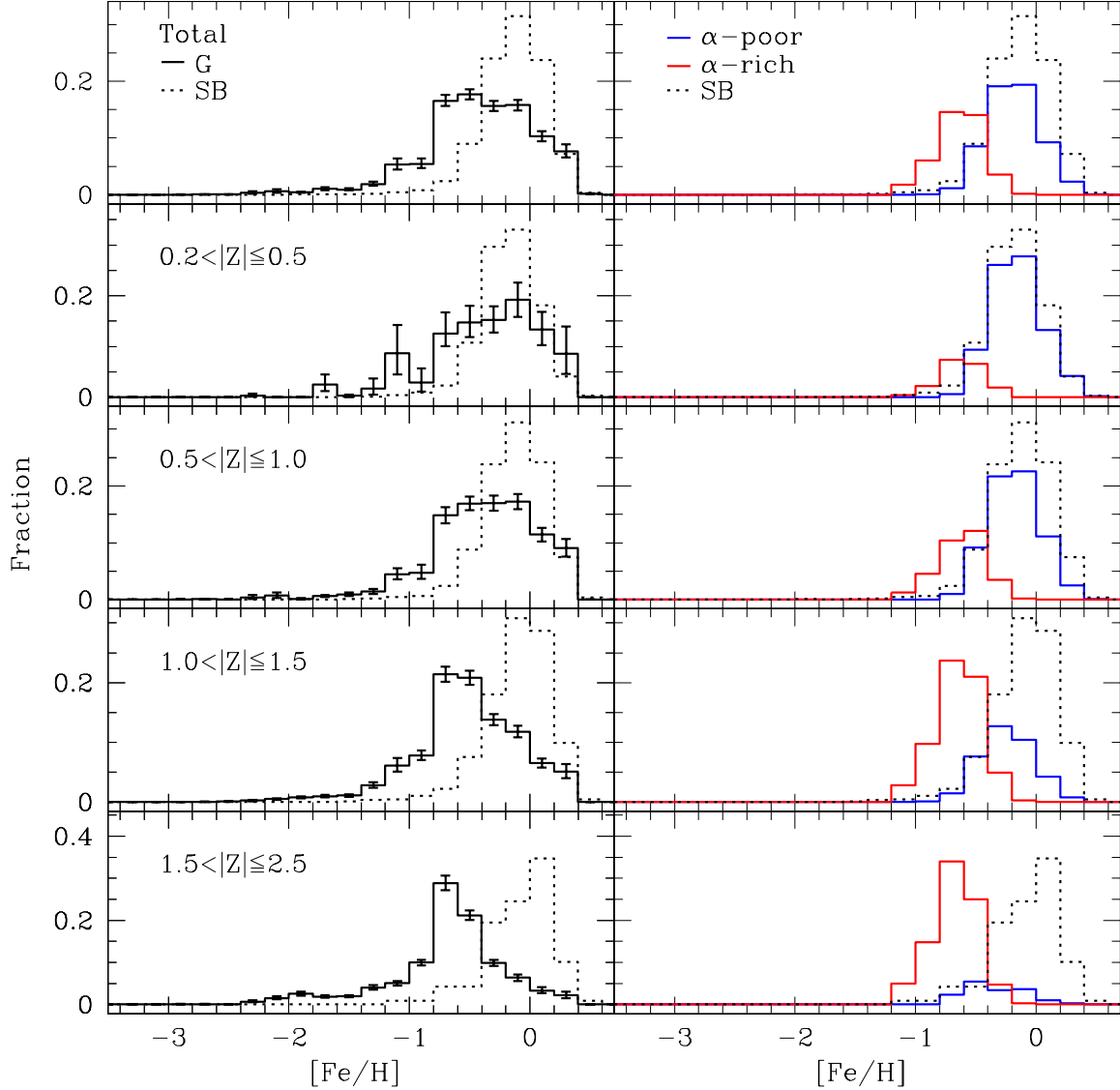


Fig. 21.— Comparison of the distribution of G-dwarf stars in the SEGUE sample (solid black) to that in the SB Galaxy models (dashed black) in the left column. Both sample and model are limited to distances between 1.59 and 2.29 kpc. The SB Galaxy model is significantly more metal rich than the SEGUE G-dwarf sample. This discrepancy is also seen for the K-dwarf sample. On the right side, we compare the G-dwarf distribution in the model (dashed black) to the  $\alpha$ -separated G-dwarf sample from Lee et al. (2011b). The sample with enhanced  $[\alpha/\text{Fe}]$  is shown in red; that with low  $[\alpha/\text{Fe}]$  is plotted in blue. For  $|Z|$  less than 1 kpc, the SB model is consistent with the  $\alpha$ -poor distribution. Above 1 kpc, the model is more metal-rich than this component. The general agreement with solely the  $\alpha$ -poor portion suggests that the SB models currently only recreate the chemistry of the thin-disk portion of the Galaxy.

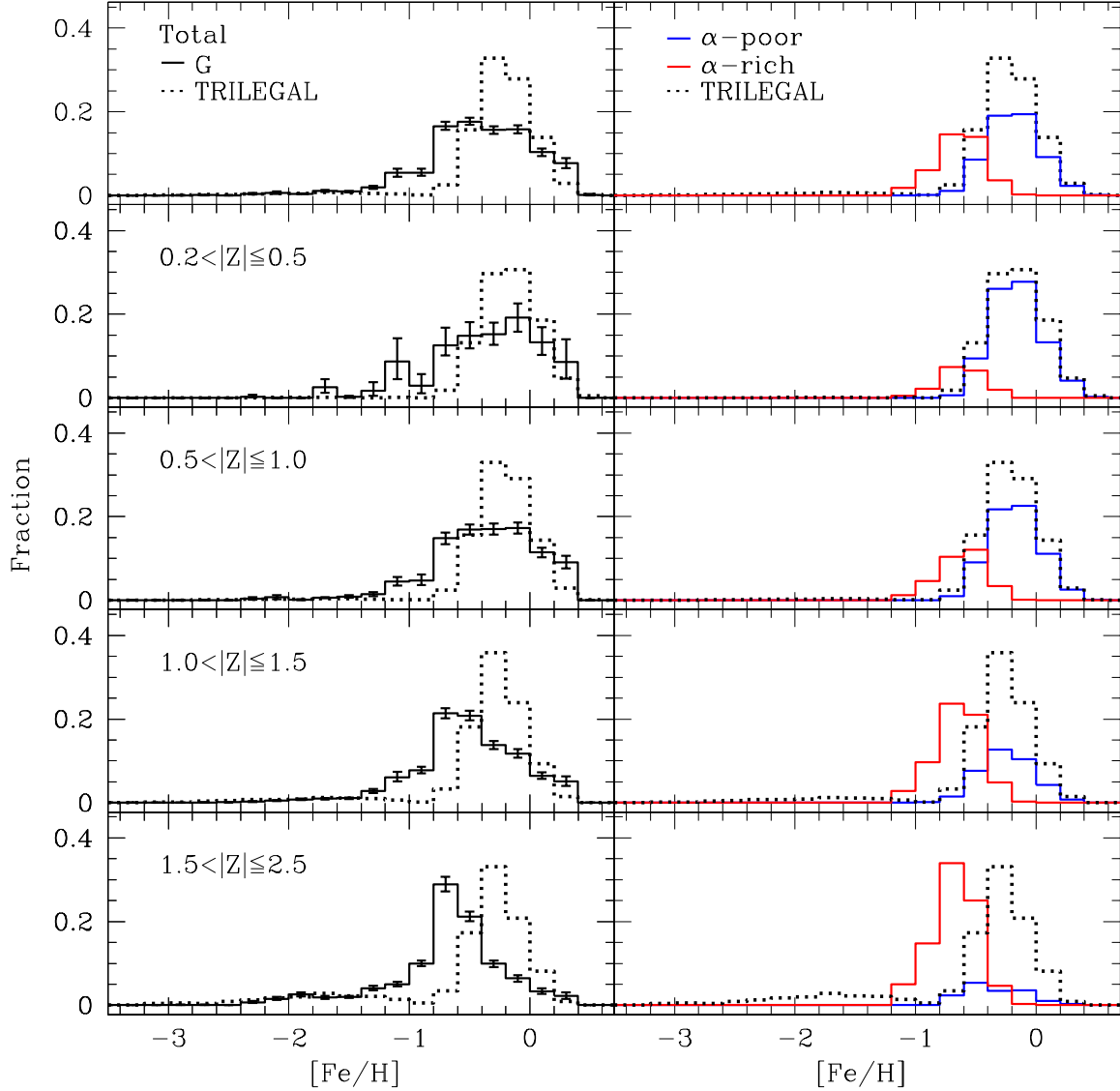


Fig. 22.— The same as Figure 21, except now for the TRILEGAL models, rather than those of Schönrich & Binney (2009a,b). This model is also more metal-rich than the SEGUE G-dwarf sample. It agrees well with the  $\alpha$ -poor  $[\text{Fe}/\text{H}]$  distribution of G dwarfs over all  $|Z|$ , implying the simulation consists primarily of thin-disk stars. In contrast to the SB models, there is a small number of stars at low metallicities, but it does not match our distribution. The comparison of SEGUE K dwarfs with the TRILEGAL model shows a similar discrepancy.

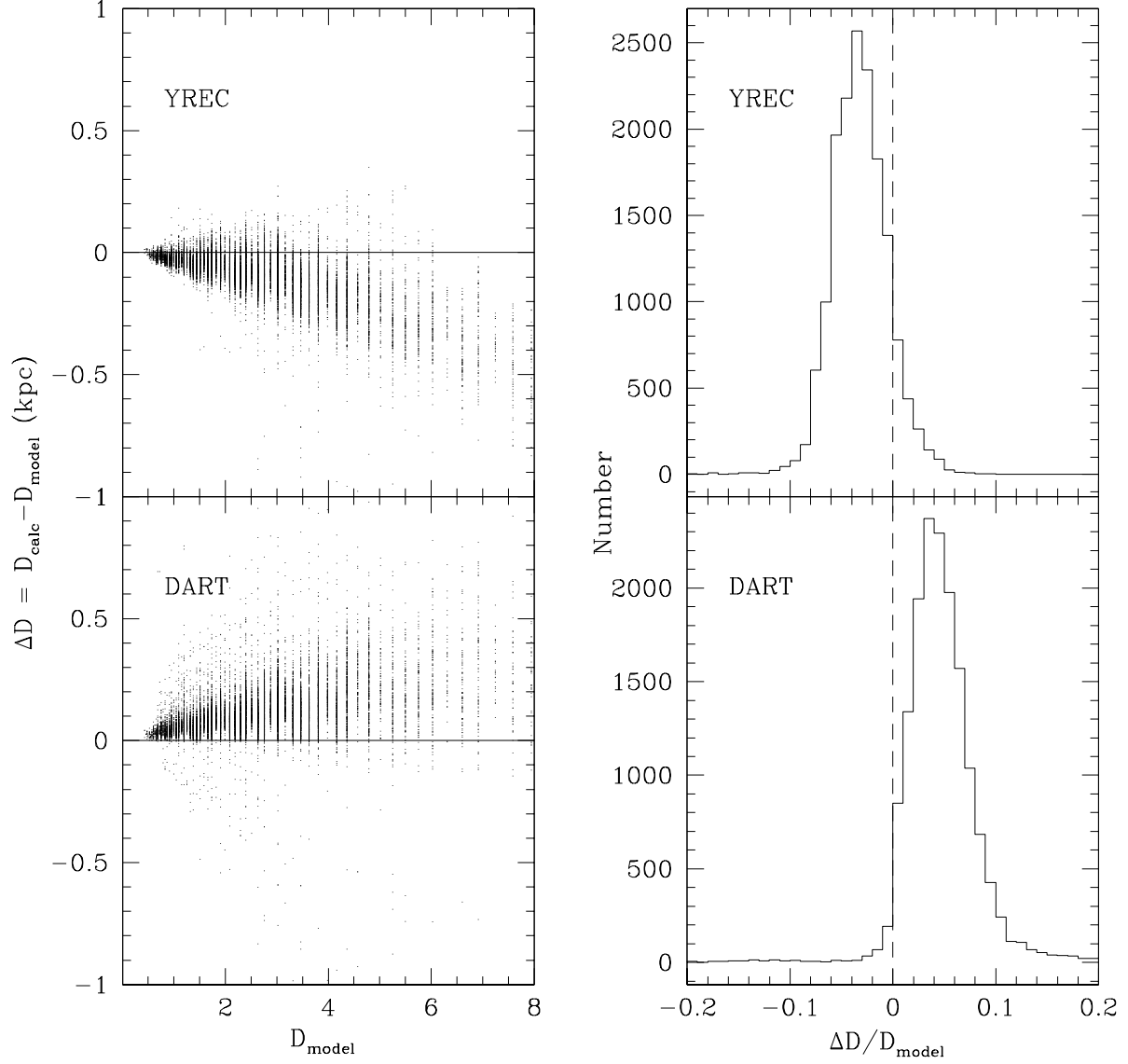


Fig. 23.— The distances calculated for the TRILEGAL model targets along a particular line of sight compared to their provided distances. Each of these targets has a metallicity between 0.4 and  $-3.5$ , color and magnitude within the expected range for SEGUE G and K dwarfs, and  $\log g \geq 4.1$ , ensuring it is on the main sequence. The top row shows results using the YREC isochrones assuming an age of 10 Gyrs. The bottom row is the results using Dartmouth isochrones, again assuming an age of 10 Gyr.

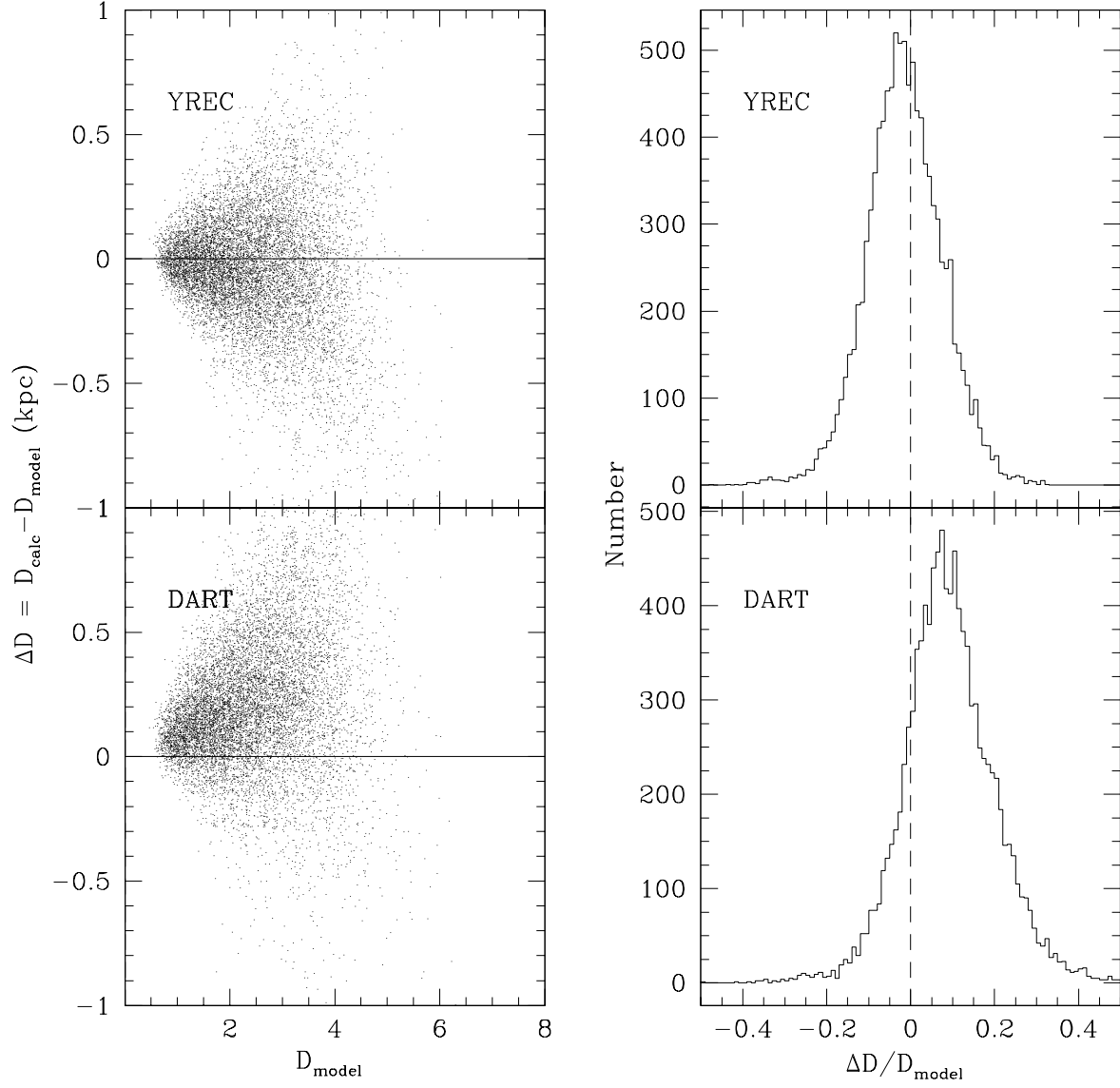


Fig. 24.— Similar to Figure 23, except for the SB models. The top row shows results using the YREC isochrones assuming an age of 10 Gyrs. The bottom row is the results using Dartmouth isochrones.



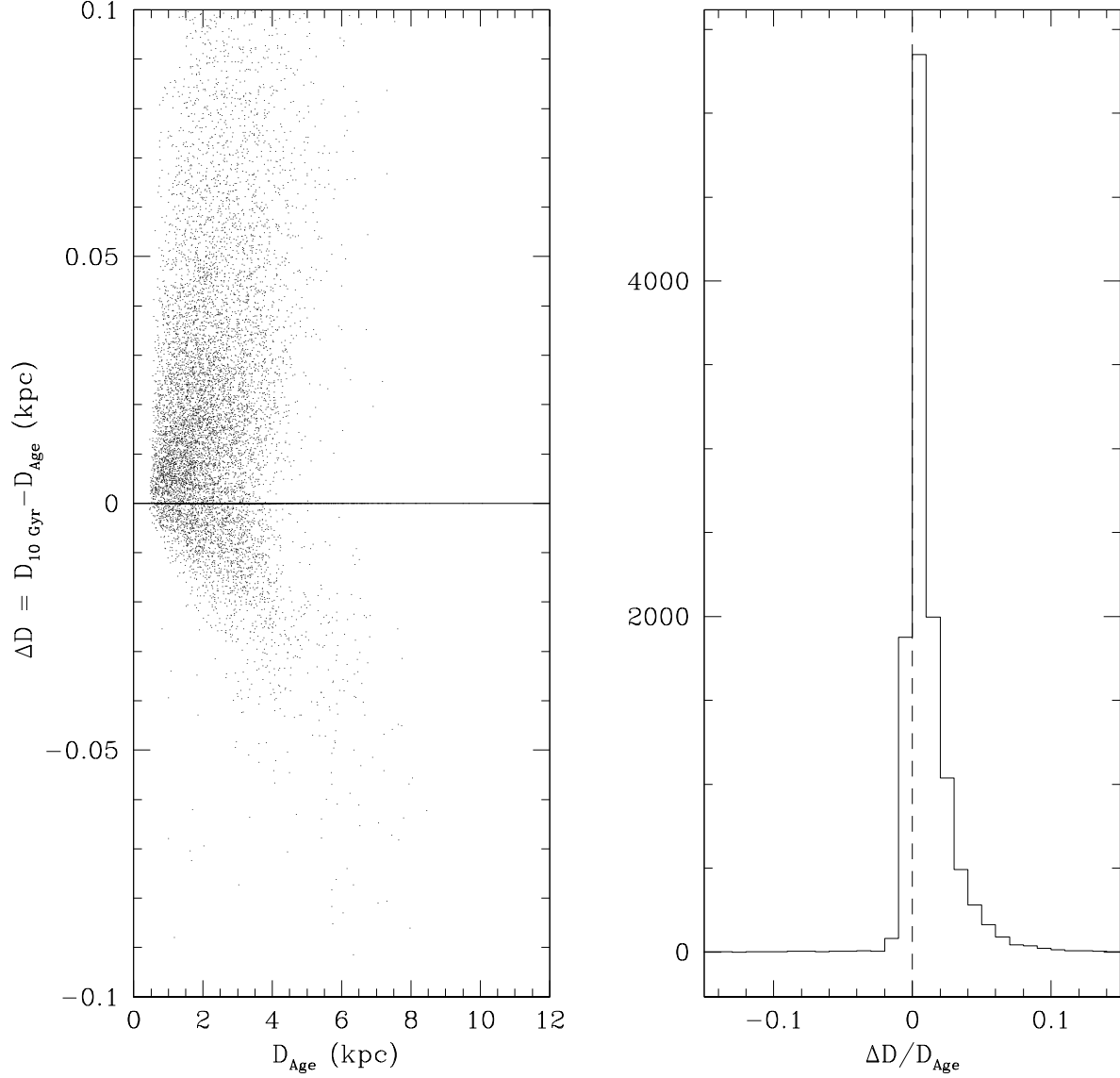


Fig. 25.— Quantifying the effect of our age assumptions on our distance calculations. The left hand side shows the difference in calculated distance when one assumes an age of 10 Gyr as opposed to using the age specified by the SB Galaxy model. For younger stars, assuming an age of 10 Gyr will systematically overestimate stellar distances, although it is only a maximum difference of around 0.1 kpc. The right hand plot presents the distribution of the percent difference caused by our age assumptions. Our calculated distances are most frequently overestimated by around  $1 \pm 2\%$  due to age assumptions.

Table 1. Cluster Metallicities determined with the Optimized SSPP

Cluster	Literature	[Fe/H]	$(g - r)$
		All	
M92	-2.25	-2.23±0.22	-2.32±0.09
M3	-1.55	-1.55±0.18	-1.58±0.16
M71	-0.79	-0.78±0.12	-0.77±0.13
NGC 2420	-0.20 <sup>a</sup>	-0.28±0.13	-0.26±0.13
NGC 2158	-0.26	-0.26±0.10	-0.30±0.09
M67	0.05 <sup>b</sup>	0.06±0.07	0.03±0.10
NGC 6791	0.31	0.40±0.12	0.36±0.09

<sup>a</sup>Jacobson et al. (2011)

<sup>b</sup>Randich et al. (2006)

Note. — The mean and  $\sigma$  [Fe/H] values of cluster members based upon the optimized version of the SSPP. All literature values are from Smolinski et al. (2011) unless otherwise noted. The calculated metallicities are similar to the literature values demonstrating that this SSPP version accurately determines stellar parameters. The “ $(g - r)$ ” column isolates members with colors in the appropriate range for G and K dwarfs. These values are not significantly different than those for the whole cluster sample.

Table 2. Cluster Distances

Cluster	[Fe/H]	E(B-V)	Assumed Age Gyr	Literature kpc	Photometric $\pi$ kpc	Dartmouth kpc	YREC kpc
M13	-1.54	0.017	14	7.7	7.71±0.78	7.75±0.95	8.01±1.01
M67	+0.02	0.032	4	0.91	0.93±0.10	0.87±0.10	0.87±0.12
NGC 2420	-0.44	0.041	2	3.09	2.73±0.26	2.82±0.25	2.39±0.19
NGC 6791	+0.30	0.117	4	4.10	3.83±0.69	3.55±1.04	3.47±0.52

Note. — The parameters and distances determined for the test clusters. The E(B-V) is based on Schlegel et al. (1998), as listed in Lee et al. (2008b). The listed metallicity and literature distances are from Harris (1996) for the three globular clusters and WEBDA for the two open clusters. Note that these metallicity values are slightly different than those found using the SSPP listed in Table 1 due to the different SSPP version used for these measurements..

Table 3. Total Metallicity Distribution Functions of G and K dwarfs over Different Distance Ranges

[Fe/H]	G dwarfs				K dwarfs			
	1.59≤d≤2.29 kpc		1.59≤d≤1.84 kpc		1.18≤d≤1.84 kpc		1.59≤d≤1.84 kpc	
	Raw	Weighted	Raw	Weighted	Raw	Weighted	Raw	Weighted
−3.3	0 <sup>+0</sup> <sub>−0</sub>	0 <sup>+0</sup> <sub>−0</sub>	0 <sup>+0</sup> <sub>−0</sub>	0 <sup>+0</sup> <sub>−0</sub>	1 <sup>+1</sup> <sub>−1</sub>	12 <sup>+19</sup> <sub>−9</sub>	0 <sup>+0</sup> <sub>−0</sub>	0 <sup>+0</sup> <sub>−0</sub>
−3.1	2 <sup>+1</sup> <sub>−1</sub>	4 <sup>+4</sup> <sub>−3</sub>	0 <sup>+0</sup> <sub>−0</sub>	0 <sup>+0</sup> <sub>−0</sub>	6 <sup>+3</sup> <sub>−3</sub>	34 <sup>+20</sup> <sub>−16</sub>	4 <sup>+2</sup> <sub>−2</sub>	26 <sup>+20</sup> <sub>−14</sub>
−2.9	3 <sup>+2</sup> <sub>−2</sub>	15 <sup>+15</sup> <sub>−10</sub>	0 <sup>+0</sup> <sub>−0</sub>	0 <sup>+0</sup> <sub>−0</sub>	5 <sup>+2</sup> <sub>−2</sub>	41 <sup>+24</sup> <sub>−20</sub>	2 <sup>+1</sup> <sub>−1</sub>	14 <sup>+11</sup> <sub>−10</sub>
−2.7	8 <sup>+3</sup> <sub>−3</sub>	31 <sup>+24</sup> <sub>−16</sub>	4 <sup>+2</sup> <sub>−2</sub>	9 <sup>+6</sup> <sub>−4</sub>	17 <sup>+4</sup> <sub>−4</sub>	138 <sup>+80</sup> <sub>−57</sub>	4 <sup>+2</sup> <sub>−2</sub>	49 <sup>+41</sup> <sub>−29</sub>
−2.5	12 <sup>+3</sup> <sub>−4</sub>	27 <sup>+10</sup> <sub>−10</sub>	4 <sup>+2</sup> <sub>−2</sub>	6 <sup>+5</sup> <sub>−3</sub>	21 <sup>+5</sup> <sub>−4</sub>	110 <sup>+44</sup> <sub>−33</sub>	5 <sup>+2</sup> <sub>−2</sub>	32 <sup>+22</sup> <sub>−16</sub>
−2.3	32 <sup>+6</sup> <sub>−5</sub>	195 <sup>+122</sup> <sub>−88</sub>	13 <sup>+4</sup> <sub>−4</sub>	36 <sup>+30</sup> <sub>−20</sub>	54 <sup>+8</sup> <sub>−7</sub>	623 <sup>+176</sup> <sub>−161</sub>	20 <sup>+4</sup> <sub>−4</sub>	271 <sup>+152</sup> <sub>−115</sub>
−2.1	70 <sup>+8</sup> <sub>−9</sub>	323 <sup>+189</sup> <sub>−120</sub>	22 <sup>+5</sup> <sub>−5</sub>	35 <sup>+12</sup> <sub>−10</sub>	98 <sup>+11</sup> <sub>−8</sub>	860 <sup>+231</sup> <sub>−178</sub>	49 <sup>+7</sup> <sub>−6</sub>	462 <sup>+172</sup> <sub>−136</sub>
−1.9	106 <sup>+10</sup> <sub>−10</sub>	211 <sup>+43</sup> <sub>−34</sub>	29 <sup>+5</sup> <sub>−6</sub>	77 <sup>+37</sup> <sub>−28</sub>	161 <sup>+13</sup> <sub>−13</sub>	2100 <sup>+711</sup> <sub>−599</sub>	68 <sup>+8</sup> <sub>−8</sub>	818 <sup>+524</sup> <sub>−378</sub>
−1.7	141 <sup>+12</sup> <sub>−12</sub>	563 <sup>+152</sup> <sub>−124</sub>	56 <sup>+7</sup> <sub>−8</sub>	274 <sup>+133</sup> <sub>−96</sub>	185 <sup>+13</sup> <sub>−13</sub>	1292 <sup>+564</sup> <sub>−371</sub>	64 <sup>+7</sup> <sub>−8</sub>	276 <sup>+68</sup> <sub>−53</sub>
−1.5	198 <sup>+14</sup> <sub>−14</sub>	482 <sup>+106</sup> <sub>−88</sub>	72 <sup>+8</sup> <sub>−9</sub>	218 <sup>+77</sup> <sub>−62</sub>	236 <sup>+15</sup> <sub>−14</sub>	1868 <sup>+246</sup> <sub>−231</sub>	97 <sup>+10</sup> <sub>−9</sub>	696 <sup>+166</sup> <sub>−123</sub>
−1.3	291 <sup>+18</sup> <sub>−17</sub>	1001 <sup>+217</sup> <sub>−184</sub>	108 <sup>+10</sup> <sub>−11</sub>	384 <sup>+168</sup> <sub>−126</sub>	236 <sup>+15</sup> <sub>−16</sub>	1720 <sup>+374</sup> <sub>−304</sub>	85 <sup>+9</sup> <sub>−9</sub>	768 <sup>+291</sup> <sub>−232</sub>
−1.1	530 <sup>+21</sup> <sub>−22</sub>	2822 <sup>+548</sup> <sub>−475</sub>	173 <sup>+13</sup> <sub>−12</sub>	362 <sup>+76</sup> <sub>−59</sub>	436 <sup>+23</sup> <sub>−18</sub>	3474 <sup>+442</sup> <sub>−407</sub>	173 <sup>+14</sup> <sub>−13</sub>	1373 <sup>+229</sup> <sub>−201</sub>
−0.9	1002 <sup>+30</sup> <sub>−31</sub>	2865 <sup>+481</sup> <sub>−387</sub>	376 <sup>+19</sup> <sub>−20</sub>	882 <sup>+238</sup> <sub>−162</sub>	715 <sup>+30</sup> <sub>−25</sub>	5535 <sup>+475</sup> <sub>−449</sub>	265 <sup>+18</sup> <sub>−16</sub>	2613 <sup>+396</sup> <sub>−344</sub>
−0.7	1720 <sup>+42</sup>	8685 <sup>+574</sup>	674 <sup>+28</sup>	2938 <sup>+348</sup>	931 <sup>+33</sup>	1.213×10 <sup>4</sup> <sup>+940</sup>	337 <sup>+21</sup>	5034 <sup>+793</sup>

Table 3—Continued

[Fe/H]	G dwarfs				K dwarfs			
	1.59≤d≤2.29 kpc		1.59≤d≤1.84 kpc		1.18≤d≤1.84 kpc		1.59≤d≤1.84 kpc	
	Raw	Weighted	Raw	Weighted	Raw	Weighted	Raw	Weighted
	−41	−466	−23	−202	−29	−809	−16	−618
−0.5	1550 <sup>+35</sup> <sub>−38</sub>	9286 <sup>+485</sup> <sub>−438</sub>	620 <sup>+23</sup> <sub>−23</sub>	3460 <sup>+296</sup> <sub>−259</sub>	905 <sup>+27</sup> <sub>−29</sub>	1.619×10 <sup>4</sup> <sup>+1247</sup> <sub>−1099</sub>	315 <sup>+17</sup> <sub>−16</sub>	6615 <sup>+910</sup> <sub>−737</sub>
−0.3	1021 <sup>+32</sup> <sub>−34</sub>	8238 <sup>+442</sup> <sub>−489</sub>	422 <sup>+20</sup> <sub>−22</sub>	2666 <sup>+240</sup> <sub>−220</sub>	688 <sup>+24</sup> <sub>−25</sub>	1.695×10 <sup>4</sup> <sup>+916</sup> <sub>−898</sub>	226 <sup>+14</sup> <sub>−14</sub>	5757 <sup>+541</sup> <sub>−522</sub>
−0.1	709 <sup>+26</sup> <sub>−27</sub>	8307 <sup>+500</sup> <sub>−487</sub>	334 <sup>+19</sup> <sub>−18</sub>	3316 <sup>+328</sup> <sub>−285</sub>	446 <sup>+23</sup> <sub>−19</sub>	1.403×10 <sup>4</sup> <sup>+1088</sup> <sub>−1059</sub>	129 <sup>+12</sup> <sub>−11</sub>	4974 <sup>+694</sup> <sub>−624</sub>
0.1	330 <sup>+18</sup> <sub>−18</sub>	5432 <sup>+473</sup> <sub>−473</sub>	158 <sup>+13</sup> <sub>−12</sub>	2224 <sup>+279</sup> <sub>−273</sub>	178 <sup>+14</sup> <sub>−13</sub>	7903 <sup>+934</sup> <sub>−915</sub>	58 <sup>+7</sup> <sub>−8</sub>	3218 <sup>+645</sup> <sub>−591</sub>
0.3	107 <sup>+11</sup> <sub>−10</sub>	4022 <sup>+659</sup> <sub>−573</sub>	54 <sup>+8</sup> <sub>−7</sub>	1633 <sup>+358</sup> <sub>−291</sub>	88 <sup>+9</sup> <sub>−10</sub>	6494 <sup>+1127</sup> <sub>−976</sub>	23 <sup>+5</sup> <sub>−5</sub>	2460 <sup>+775</sup> <sub>−665</sub>
0.5	2 <sup>+1</sup> <sub>−1</sub>	82 <sup>+73</sup> <sub>−56</sub>	2 <sup>+1</sup> <sub>−1</sub>	82 <sup>+73</sup> <sub>−56</sub>	0 <sup>+0</sup> <sub>−0</sub>	0 <sup>+0</sup> <sub>−0</sub>	0 <sup>+0</sup> <sub>−0</sub>	0 <sup>+0</sup> <sub>−0</sub>

Note. — The number of G and K dwarfs in each metallicity bin using different distance limits. The Raw numbers are the original spectroscopic sample; the Weighted are once we have applied our corrections that accounting for SEGUE target selection effects. The listed errors reflect the uncertainties in each bin determined from a bootstrap analysis over 500 iterations.

Table 4. Radial Gradients for G and K dwarfs

$ Z $ (kpc)	G dwarfs		K dwarfs		C11
	Weighted	TRILEGAL	Weighted	TRILEGAL	
0.2–0.5	$0.05^{+0.06}_{-0.10}$	0.05	$-0.03^{+0.07}_{-0.05}$	0.05	$-0.064^{+0.015}_{-0.0041}$
0.5–1.0	$0.02^{+0.04}_{-0.01}$	0.04	$0.03^{+0.04}_{-0.03}$	0.05	$-0.013^{+0.0093}_{-0.0016}$
1.0–1.5	$0.04^{+0.04}_{-0.02}$	0.04	$0.05^{+0.05}_{-0.03}$	0.05	$+0.0028^{+0.0071}_{-0.0052}$
1.5–2.5	$0.05^{+0.04}_{-0.01}$	0.04	$0.10^{+0.10}_{-0.09}$	0.05	

Note. — The radial gradient for G and K dwarfs at different heights above the plane of the Galaxy, accounting for the SEGUE target selection biases. These parameters are derived from the G-dwarf sample between distances of 1.59 and 2.29 kpc, and the K-dwarf stars between 1.18 and 1.84 kpc. The listed uncertainties on the slope reflect the standard deviations in the calculated slopes from our bootstrap technique. We also list the induced slope that originates in correlated metallicity and distance errors, which we estimate using TRILEGAL modeled lines of sight. The final column lists the radial metallicity gradients estimated with main sequence turn off stars at low latitudes by Cheng et al. (2011).

Table 5. The Metallicity Distribution Functions of G dwarfs over Different Ranges of  $|Z|$  for  $1.59 \leq d \leq 2.29$  kpc.

[Fe/H]	$0.0 \leq  Z  < 0.5$ kpc		$0.5 \leq  Z  < 1.0$ kpc		$1.0 \leq  Z  < 1.5$ kpc		$1.5 \leq  Z  < 2.5$ kpc	
	Raw	Weighted	Raw	Weighted	Raw	Weighted	Raw	Weighted
–3.3	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>
–3.1	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	1 <sup>+1</sup> <sub>–1</sub>	4 <sup>+4</sup> <sub>–4</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	1 <sup>+1</sup> <sub>–1</sub>	1 <sup>+1</sup> <sub>–1</sub>
–2.9	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	1 <sup>+1</sup> <sub>–1</sub>	11 <sup>+12</sup> <sub>–11</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	2 <sup>+1</sup> <sub>–1</sub>	3 <sup>+3</sup> <sub>–2</sub>
–2.7	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	2 <sup>+1</sup> <sub>–1</sub>	22 <sup>+25</sup> <sub>–15</sub>	3 <sup>+2</sup> <sub>–2</sub>	6 <sup>+5</sup> <sub>–3</sub>	3 <sup>+2</sup> <sub>–2</sub>	3 <sup>+2</sup> <sub>–2</sub>
–2.5	1 <sup>+1</sup> <sub>–1</sub>	0 <sup>+0</sup> <sub>–0</sub>	3 <sup>+2</sup> <sub>–2</sub>	13 <sup>+8</sup> <sub>–7</sub>	4 <sup>+2</sup> <sub>–2</sub>	11 <sup>+8</sup> <sub>–6</sub>	4 <sup>+2</sup> <sub>–2</sub>	3 <sup>+2</sup> <sub>–1</sub>
–2.3	1 <sup>+1</sup> <sub>–1</sub>	24 <sup>+37</sup> <sub>–17</sub>	5 <sup>+2</sup> <sub>–2</sub>	121 <sup>+122</sup> <sub>–83</sub>	11 <sup>+3</sup> <sub>–3</sub>	23 <sup>+10</sup> <sub>–8</sub>	15 <sup>+4</sup> <sub>–4</sub>	26 <sup>+11</sup> <sub>–9</sub>
–2.1	1 <sup>+1</sup> <sub>–1</sub>	0 <sup>+0</sup> <sub>–0</sub>	8 <sup>+3</sup> <sub>–3</sub>	219 <sup>+185</sup> <sub>–119</sub>	22 <sup>+5</sup> <sub>–4</sub>	47 <sup>+15</sup> <sub>–12</sub>	39 <sup>+6</sup> <sub>–7</sub>	56 <sup>+15</sup> <sub>–12</sub>
–1.9	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	7 <sup>+3</sup> <sub>–3</sub>	43 <sup>+37</sup> <sub>–25</sub>	40 <sup>+6</sup> <sub>–6</sub>	77 <sup>+17</sup> <sub>–15</sub>	59 <sup>+8</sup> <sub>–7</sub>	92 <sup>+18</sup> <sub>–16</sub>
–1.7	3 <sup>+2</sup> <sub>–2</sub>	206 <sup>+159</sup> <sub>–106</sub>	29 <sup>+5</sup> <sub>–5</sub>	195 <sup>+50</sup> <sub>–46</sub>	56 <sup>+8</sup> <sub>–8</sub>	94 <sup>+19</sup> <sub>–17</sub>	53 <sup>+7</sup> <sub>–7</sub>	68 <sup>+11</sup> <sub>–12</sub>
–1.5	1 <sup>+1</sup> <sub>–1</sub>	22 <sup>+21</sup> <sub>–22</sub>	37 <sup>+6</sup> <sub>–6</sub>	285 <sup>+101</sup> <sub>–80</sub>	67 <sup>+8</sup> <sub>–8</sub>	104 <sup>+20</sup> <sub>–18</sub>	93 <sup>+10</sup> <sub>–9</sub>	71 <sup>+11</sup> <sub>–9</sub>
–1.3	2 <sup>+1</sup> <sub>–1</sub>	136 <sup>+167</sup> <sub>–95</sub>	35 <sup>+6</sup> <sub>–6</sub>	452 <sup>+150</sup> <sub>–136</sub>	112 <sup>+11</sup> <sub>–11</sub>	268 <sup>+45</sup> <sub>–42</sub>	142 <sup>+12</sup> <sub>–12</sub>	145 <sup>+21</sup> <sub>–18</sub>
–1.1	6 <sup>+2</sup> <sub>–2</sub>	704 <sup>+456</sup> <sub>–340</sub>	79 <sup>+8</sup> <sub>–9</sub>	1398 <sup>+336</sup> <sub>–282</sub>	198 <sup>+15</sup> <sub>–13</sub>	582 <sup>+123</sup> <sub>–100</sub>	247 <sup>+15</sup> <sub>–15</sub>	182 <sup>+21</sup> <sub>–18</sub>
–0.9	8 <sup>+3</sup> <sub>–3</sub>	236 <sup>+228</sup> <sub>–142</sub>	127 <sup>+11</sup> <sub>–11</sub>	1484 <sup>+433</sup> <sub>–329</sub>	382 <sup>+20</sup> <sub>–19</sub>	742 <sup>+79</sup> <sub>–73</sub>	485 <sup>+21</sup> <sub>–23</sub>	361 <sup>+23</sup> <sub>–24</sub>
–0.7	25 <sup>+6</sup> <sub>–5</sub>	1026 <sup>+338</sup> <sub>–203</sub>	297 <sup>+16</sup> <sub>–18</sub>	4638 <sup>+444</sup> <sub>–442</sub>	669 <sup>+27</sup> <sub>–24</sub>	2034 <sup>+121</sup> <sub>–115</sub>	729 <sup>+27</sup> <sub>–27</sub>	1045 <sup>+65</sup> <sub>–60</sub>
–0.5	36 <sup>+6</sup> <sub>–6</sub>	1205 <sup>+267</sup> <sub>–236</sub>	377 <sup>+19</sup> <sub>–18</sub>	5291 <sup>+401</sup> <sub>–361</sub>	632 <sup>+23</sup> <sub>–25</sub>	1981 <sup>+111</sup> <sub>–111</sub>	505 <sup>+23</sup> <sub>–23</sub>	768 <sup>+40</sup> <sub>–41</sub>
–0.3	40 <sup>+7</sup> <sub>–6</sub>	1239 <sup>+223</sup> <sub>–204</sub>	345 <sup>+19</sup> <sub>–19</sub>	5320 <sup>+424</sup> <sub>–419</sub>	410 <sup>+20</sup> <sub>–22</sub>	1314 <sup>+90</sup> <sub>–91</sub>	226 <sup>+14</sup> <sub>–16</sub>	360 <sup>+26</sup> <sub>–28</sub>
–0.1	44 <sup>+6</sup> <sub>–6</sub>	1565 <sup>+278</sup> <sub>–278</sub>	317 <sup>+18</sup> <sub>–18</sub>	5402 <sup>+411</sup> <sub>–406</sub>	252 <sup>+15</sup> <sub>–14</sub>	1118 <sup>+97</sup> <sub>–90</sub>	96 <sup>+9</sup> <sub>–11</sub>	232 <sup>+26</sup> <sub>–29</sub>
0.1	23 <sup>+5</sup> <sub>–5</sub>	1087 <sup>+286</sup> <sub>–254</sub>	172 <sup>+12</sup> <sub>–12</sub>	3585 <sup>+366</sup> <sub>–370</sub>	101 <sup>+10</sup> <sub>–10</sub>	618 <sup>+75</sup> <sub>–71</sub>	34 <sup>+6</sup> <sub>–6</sub>	121 <sup>+27</sup> <sub>–22</sub>
0.3	8 <sup>+3</sup> <sub>–3</sub>	700 <sup>+437</sup> <sub>–325</sub>	55 <sup>+8</sup> <sub>–7</sub>	2831 <sup>+515</sup> <sub>–453</sub>	36 <sup>+6</sup> <sub>–7</sub>	489 <sup>+114</sup> <sub>–107</sub>	8 <sup>+3</sup> <sub>–3</sub>	79 <sup>+33</sup> <sub>–27</sub>
0.5	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	2 <sup>+1</sup> <sub>–1</sub>	2 <sup>+1</sup> <sub>–1</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>

Note. — The G-dwarf raw and weighted metallicity distribution function for different ranges of  $|Z|$ . This is for the G dwarf sample limited to distances between 1.59 and 2.29 kpc.

Table 6. The Metallicity Distribution Functions of K dwarfs over Different ranges of  $|Z|$  for  $1.18 \leq d \leq 1.84$  kpc.

[Fe/H]	$0.0 \leq  Z  < 0.5$ kpc		$0.5 \leq  Z  < 1.0$ kpc		$1.0 \leq  Z  < 1.5$ kpc		$1.5 \leq  Z  < 2.5$ kpc	
	Raw	Weighted	Raw	Weighted	Raw	Weighted	Raw	Weighted
–3.3	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	1 <sup>+1</sup> <sub>–1</sub>	12 <sup>+19</sup> <sub>–9</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>
–3.1	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	1 <sup>+1</sup> <sub>–1</sub>	14 <sup>+22</sup> <sub>–10</sub>	3 <sup>+2</sup> <sub>–2</sub>	9 <sup>+6</sup> <sub>–5</sub>	2 <sup>+2</sup> <sub>–1</sub>	10 <sup>+10</sup> <sub>–7</sub>
–2.9	1 <sup>+1</sup> <sub>–1</sub>	12 <sup>+12</sup> <sub>–12</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	2 <sup>+2</sup> <sub>–1</sub>	15 <sup>+19</sup> <sub>–11</sub>	2 <sup>+1</sup> <sub>–1</sub>	14 <sup>+11</sup> <sub>–10</sub>
–2.7	1 <sup>+1</sup> <sub>–1</sub>	55 <sup>+91</sup> <sub>–39</sub>	4 <sup>+2</sup> <sub>–2</sub>	45 <sup>+42</sup> <sub>–28</sub>	11 <sup>+3</sup> <sub>–3</sub>	28 <sup>+9</sup> <sub>–9</sub>	1 <sup>+1</sup> <sub>–1</sub>	11 <sup>+18</sup> <sub>–8</sub>
–2.5	1 <sup>+1</sup> <sub>–1</sub>	31 <sup>+48</sup> <sub>–22</sub>	6 <sup>+3</sup> <sub>–2</sub>	36 <sup>+23</sup> <sub>–17</sub>	14 <sup>+4</sup> <sub>–4</sub>	43 <sup>+16</sup> <sub>–13</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>
–2.3	2 <sup>+1</sup> <sub>–1</sub>	46 <sup>+47</sup> <sub>–31</sub>	23 <sup>+5</sup> <sub>–5</sub>	453 <sup>+173</sup> <sub>–155</sub>	26 <sup>+5</sup> <sub>–5</sub>	114 <sup>+32</sup> <sub>–26</sub>	3 <sup>+2</sup> <sub>–2</sub>	10 <sup>+8</sup> <sub>–6</sub>
–2.1	8 <sup>+3</sup> <sub>–3</sub>	234 <sup>+139</sup> <sub>–104</sub>	23 <sup>+5</sup> <sub>–5</sub>	415 <sup>+184</sup> <sub>–136</sub>	54 <sup>+8</sup> <sub>–7</sub>	173 <sup>+36</sup> <sub>–25</sub>	13 <sup>+3</sup> <sub>–4</sub>	37 <sup>+14</sup> <sub>–11</sub>
–1.9	8 <sup>+3</sup> <sub>–3</sub>	1264 <sup>+720</sup> <sub>–574</sub>	54 <sup>+7</sup> <sub>–7</sub>	501 <sup>+124</sup> <sub>–109</sub>	81 <sup>+9</sup> <sub>–9</sub>	269 <sup>+43</sup> <sub>–38</sub>	18 <sup>+4</sup> <sub>–4</sub>	66 <sup>+29</sup> <sub>–21</sub>
–1.7	8 <sup>+3</sup> <sub>–3</sub>	116 <sup>+49</sup> <sub>–39</sub>	58 <sup>+7</sup> <sub>–7</sub>	819 <sup>+557</sup> <sub>–375</sub>	101 <sup>+10</sup> <sub>–10</sub>	297 <sup>+48</sup> <sub>–43</sub>	18 <sup>+4</sup> <sub>–4</sub>	59 <sup>+20</sup> <sub>–18</sub>
–1.5	13 <sup>+4</sup> <sub>–3</sub>	431 <sup>+157</sup> <sub>–140</sub>	86 <sup>+10</sup> <sub>–9</sub>	922 <sup>+198</sup> <sub>–173</sub>	114 <sup>+10</sup> <sub>–11</sub>	434 <sup>+72</sup> <sub>–66</sub>	23 <sup>+4</sup> <sub>–5</sub>	82 <sup>+26</sup> <sub>–23</sub>
–1.3	11 <sup>+3</sup> <sub>–4</sub>	197 <sup>+106</sup> <sub>–90</sub>	69 <sup>+8</sup> <sub>–9</sub>	1032 <sup>+352</sup> <sub>–275</sub>	134 <sup>+12</sup> <sub>–11</sub>	424 <sup>+62</sup> <sub>–53</sub>	22 <sup>+5</sup> <sub>–5</sub>	67 <sup>+24</sup> <sub>–19</sub>
–1.1	28 <sup>+5</sup> <sub>–5</sub>	1059 <sup>+370</sup> <sub>–331</sub>	157 <sup>+14</sup> <sub>–11</sub>	1390 <sup>+240</sup> <sub>–199</sub>	213 <sup>+14</sup> <sub>–14</sub>	901 <sup>+138</sup> <sub>–111</sub>	38 <sup>+7</sup> <sub>–6</sub>	125 <sup>+31</sup> <sub>–23</sub>
–0.9	35 <sup>+6</sup> <sub>–6</sub>	1007 <sup>+338</sup> <sub>–269</sub>	242 <sup>+16</sup> <sub>–15</sub>	2709 <sup>+354</sup> <sub>–328</sub>	389 <sup>+22</sup> <sub>–19</sub>	1688 <sup>+162</sup> <sub>–146</sub>	49 <sup>+7</sup> <sub>–7</sub>	131 <sup>+36</sup> <sub>–30</sub>
–0.7	60 <sup>+8</sup> <sub>–7</sub>	2420 <sup>+508</sup> <sub>–474</sub>	342 <sup>+19</sup> <sub>–17</sub>	6080 <sup>+758</sup> <sub>–612</sub>	475 <sup>+23</sup> <sub>–22</sub>	3331 <sup>+264</sup> <sub>–230</sub>	54 <sup>+7</sup> <sub>–8</sub>	301 <sup>+56</sup> <sub>–48</sub>
–0.5	93 <sup>+9</sup> <sub>–10</sub>	4880 <sup>+954</sup> <sub>–834</sub>	414 <sup>+20</sup> <sub>–21</sub>	8105 <sup>+791</sup> <sub>–693</sub>	360 <sup>+17</sup> <sub>–18</sub>	2879 <sup>+194</sup> <sub>–197</sub>	38 <sup>+6</sup> <sub>–6</sub>	325 <sup>+91</sup> <sub>–76</sub>
–0.3	100 <sup>+9</sup> <sub>–10</sub>	5190 <sup>+726</sup> <sub>–644</sub>	376 <sup>+20</sup> <sub>–18</sub>	9635 <sup>+678</sup> <sub>–631</sub>	198 <sup>+13</sup> <sub>–15</sub>	2043 <sup>+187</sup> <sub>–207</sub>	14 <sup>+4</sup> <sub>–4</sub>	81 <sup>+29</sup> <sub>–25</sub>
–0.1	75 <sup>+9</sup> <sub>–9</sub>	4850 <sup>+804</sup> <sub>–788</sub>	257 <sup>+17</sup> <sub>–15</sub>	7815 <sup>+763</sup> <sub>–622</sub>	111 <sup>+11</sup> <sub>–11</sub>	1352 <sup>+176</sup> <sub>–168</sub>	3 <sup>+2</sup> <sub>–2</sub>	18 <sup>+18</sup> <sub>–11</sub>
0.1	33 <sup>+6</sup> <sub>–6</sub>	2767 <sup>+650</sup> <sub>–583</sub>	93 <sup>+10</sup> <sub>–10</sub>	4089 <sup>+661</sup> <sub>–604</sub>	50 <sup>+7</sup> <sub>–7</sub>	1013 <sup>+215</sup> <sub>–177</sub>	2 <sup>+2</sup> <sub>–1</sub>	34 <sup>+29</sup> <sub>–23</sub>
0.3	17 <sup>+4</sup> <sub>–4</sub>	2380 <sup>+703</sup> <sub>–630</sub>	53 <sup>+7</sup> <sub>–7</sub>	3524 <sup>+796</sup> <sub>–706</sub>	18 <sup>+4</sup> <sub>–4</sub>	591 <sup>+217</sup> <sub>–168</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>
0.5	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>

Note. — The K-dwarf raw and weighted metallicity distribution function for different ranges of  $|Z|$ . This is for the distances between 1.18 and 1.84 kpc.

Table 7. The Metallicity Distribution Functions of G dwarfs over Different Ranges of  $|Z|$  for  $1.59 \leq d \leq 1.84$  kpc.

[Fe/H]	$0.0 \leq  Z  < 0.5$ kpc		$0.5 \leq  Z  < 1.0$ kpc		$1.0 \leq  Z  < 1.5$ kpc		$1.5 \leq  Z  < 2.5$ kpc	
	Raw	Weighted	Raw	Weighted	Raw	Weighted	Raw	Weighted
–3.3	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>
–3.1	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>
–2.9	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>
–2.7	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	1 <sup>+1</sup> <sub>–1</sub>	3 <sup>+3</sup> <sub>–3</sub>	2 <sup>+2</sup> <sub>–1</sub>	6 <sup>+4</sup> <sub>–4</sub>	1 <sup>+1</sup> <sub>–1</sub>	0 <sup>+0</sup> <sub>–0</sub>
–2.5	1 <sup>+1</sup> <sub>–1</sub>	0 <sup>+0</sup> <sub>–0</sub>	1 <sup>+1</sup> <sub>–1</sub>	4 <sup>+4</sup> <sub>–4</sub>	1 <sup>+1</sup> <sub>–1</sub>	1 <sup>+1</sup> <sub>–1</sub>	1 <sup>+1</sup> <sub>–1</sub>	1 <sup>+1</sup> <sub>–1</sub>
–2.3	1 <sup>+1</sup> <sub>–1</sub>	24 <sup>+37</sup> <sub>–17</sub>	2 <sup>+1</sup> <sub>–1</sub>	2 <sup>+2</sup> <sub>–2</sub>	6 <sup>+3</sup> <sub>–2</sub>	7 <sup>+5</sup> <sub>–3</sub>	4 <sup>+2</sup> <sub>–2</sub>	2 <sup>+2</sup> <sub>–1</sub>
–2.1	1 <sup>+1</sup> <sub>–1</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	12 <sup>+4</sup> <sub>–3</sub>	27 <sup>+11</sup> <sub>–10</sub>	9 <sup>+3</sup> <sub>–3</sub>	8 <sup>+4</sup> <sub>–3</sub>
–1.9	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	4 <sup>+2</sup> <sub>–2</sub>	37 <sup>+35</sup> <sub>–26</sub>	15 <sup>+4</sup> <sub>–4</sub>	27 <sup>+9</sup> <sub>–8</sub>	10 <sup>+3</sup> <sub>–3</sub>	13 <sup>+7</sup> <sub>–5</sub>
–1.7	2 <sup>+1</sup> <sub>–1</sub>	124 <sup>+147</sup> <sub>–80</sub>	15 <sup>+4</sup> <sub>–4</sub>	109 <sup>+43</sup> <sub>–37</sub>	27 <sup>+5</sup> <sub>–5</sub>	27 <sup>+9</sup> <sub>–7</sub>	12 <sup>+3</sup> <sub>–3</sub>	15 <sup>+6</sup> <sub>–5</sub>
–1.5	1 <sup>+1</sup> <sub>–1</sub>	22 <sup>+21</sup> <sub>–22</sub>	20 <sup>+4</sup> <sub>–4</sub>	157 <sup>+73</sup> <sub>–57</sub>	29 <sup>+5</sup> <sub>–5</sub>	24 <sup>+6</sup> <sub>–5</sub>	22 <sup>+5</sup> <sub>–5</sub>	15 <sup>+5</sup> <sub>–4</sub>
–1.3	2 <sup>+1</sup> <sub>–1</sub>	136 <sup>+167</sup> <sub>–95</sub>	21 <sup>+5</sup> <sub>–5</sub>	146 <sup>+78</sup> <sub>–58</sub>	53 <sup>+7</sup> <sub>–8</sub>	76 <sup>+18</sup> <sub>–15</sub>	32 <sup>+6</sup> <sub>–6</sub>	26 <sup>+7</sup> <sub>–6</sub>
–1.1	1 <sup>+1</sup> <sub>–1</sub>	0 <sup>+0</sup> <sub>–0</sub>	30 <sup>+6</sup> <sub>–5</sub>	215 <sup>+72</sup> <sub>–58</sub>	95 <sup>+11</sup> <sub>–10</sub>	126 <sup>+23</sup> <sub>–20</sub>	47 <sup>+7</sup> <sub>–7</sub>	21 <sup>+6</sup> <sub>–5</sub>
–0.9	7 <sup>+3</sup> <sub>–3</sub>	233 <sup>+226</sup> <sub>–142</sub>	56 <sup>+7</sup> <sub>–8</sub>	346 <sup>+78</sup> <sub>–67</sub>	200 <sup>+14</sup> <sub>–14</sub>	244 <sup>+25</sup> <sub>–25</sub>	113 <sup>+10</sup> <sub>–10</sub>	58 <sup>+7</sup> <sub>–7</sub>
–0.7	15 <sup>+5</sup> <sub>–3</sub>	612 <sup>+300</sup> <sub>–162</sub>	133 <sup>+10</sup> <sub>–12</sub>	1343 <sup>+155</sup> <sub>–159</sub>	336 <sup>+19</sup> <sub>–16</sub>	800 <sup>+58</sup> <sub>–54</sub>	190 <sup>+15</sup> <sub>–13</sub>	183 <sup>+21</sup> <sub>–18</sub>
–0.5	18 <sup>+4</sup> <sub>–4</sub>	628 <sup>+205</sup> <sub>–186</sub>	178 <sup>+13</sup> <sub>–13</sub>	1948 <sup>+210</sup> <sub>–194</sub>	301 <sup>+16</sup> <sub>–17</sub>	721 <sup>+58</sup> <sub>–54</sub>	123 <sup>+11</sup> <sub>–11</sub>	172 <sup>+17</sup> <sub>–17</sub>
–0.3	19 <sup>+4</sup> <sub>–4</sub>	662 <sup>+152</sup> <sub>–158</sub>	147 <sup>+13</sup> <sub>–12</sub>	1456 <sup>+182</sup> <sub>–158</sub>	198 <sup>+13</sup> <sub>–15</sub>	475 <sup>+42</sup> <sub>–42</sub>	58 <sup>+8</sup> <sub>–8</sub>	77 <sup>+11</sup> <sub>–11</sub>
–0.1	26 <sup>+5</sup> <sub>–5</sub>	816 <sup>+231</sup> <sub>–202</sub>	148 <sup>+12</sup> <sub>–12</sub>	1994 <sup>+227</sup> <sub>–209</sub>	134 <sup>+12</sup> <sub>–11</sub>	466 <sup>+59</sup> <sub>–50</sub>	26 <sup>+5</sup> <sub>–5</sub>	50 <sup>+12</sup> <sub>–10</sub>
0.1	13 <sup>+3</sup> <sub>–4</sub>	521 <sup>+181</sup> <sub>–158</sub>	81 <sup>+9</sup> <sub>–9</sub>	1364 <sup>+204</sup> <sub>–207</sub>	52 <sup>+7</sup> <sub>–7</sub>	278 <sup>+52</sup> <sub>–44</sub>	12 <sup>+3</sup> <sub>–4</sub>	41 <sup>+14</sup> <sub>–13</sub>
0.3	3 <sup>+2</sup> <sub>–2</sub>	85 <sup>+71</sup> <sub>–49</sub>	29 <sup>+6</sup> <sub>–5</sub>	1333 <sup>+363</sup> <sub>–270</sub>	20 <sup>+4</sup> <sub>–5</sub>	264 <sup>+83</sup> <sub>–72</sub>	2 <sup>+1</sup> <sub>–1</sub>	30 <sup>+26</sup> <sub>–17</sub>
0.5	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	2 <sup>+1</sup> <sub>–1</sub>	2 <sup>+1</sup> <sub>–1</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>

Note. — The G-dwarf raw and weighted metallicity distribution function for different ranges of  $|Z|$ . This is for the distances between 1.59 and 1.84 kpc.



Table 8. The Metallicity Distribution Functions of K dwarfs over Different ranges of  $|Z|$  for  $1.59 \leq d \leq 1.84$  kpc.

[Fe/H]	$0.0 \leq  Z  < 0.5$ kpc		$0.5 \leq  Z  < 1.0$ kpc		$1.0 \leq  Z  < 1.5$ kpc		$1.5 \leq  Z  < 2.5$ kpc	
	Raw	Weighted	Raw	Weighted	Raw	Weighted	Raw	Weighted
–3.3	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>
–3.1	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	1 <sup>+1</sup> <sub>–1</sub>	14 <sup>+22</sup> <sub>–10</sub>	1 <sup>+1</sup> <sub>–1</sub>	1 <sup>+1</sup> <sub>–1</sub>	2 <sup>+2</sup> <sub>–1</sub>	10 <sup>+10</sup> <sub>–7</sub>
–2.9	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	2 <sup>+1</sup> <sub>–1</sub>	14 <sup>+11</sup> <sub>–10</sub>
–2.7	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	2 <sup>+1</sup> <sub>–1</sub>	35 <sup>+38</sup> <sub>–28</sub>	1 <sup>+1</sup> <sub>–1</sub>	2 <sup>+2</sup> <sub>–2</sub>	1 <sup>+1</sup> <sub>–1</sub>	11 <sup>+18</sup> <sub>–8</sub>
–2.5	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	1 <sup>+1</sup> <sub>–1</sub>	16 <sup>+24</sup> <sub>–12</sub>	4 <sup>+2</sup> <sub>–2</sub>	16 <sup>+11</sup> <sub>–8</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>
–2.3	1 <sup>+1</sup> <sub>–1</sub>	6 <sup>+8</sup> <sub>–4</sub>	6 <sup>+2</sup> <sub>–3</sub>	228 <sup>+151</sup> <sub>–116</sub>	10 <sup>+3</sup> <sub>–3</sub>	27 <sup>+11</sup> <sub>–9</sub>	3 <sup>+2</sup> <sub>–2</sub>	10 <sup>+8</sup> <sub>–6</sub>
–2.1	2 <sup>+1</sup> <sub>–1</sub>	127 <sup>+116</sup> <sub>–89</sub>	10 <sup>+3</sup> <sub>–3</sub>	209 <sup>+137</sup> <sub>–93</sub>	25 <sup>+5</sup> <sub>–5</sub>	91 <sup>+25</sup> <sub>–20</sub>	12 <sup>+3</sup> <sub>–4</sub>	35 <sup>+13</sup> <sub>–11</sub>
–1.9	1 <sup>+1</sup> <sub>–1</sub>	463 <sup>+424</sup> <sub>–463</sub>	15 <sup>+4</sup> <sub>–4</sub>	153 <sup>+74</sup> <sub>–56</sub>	37 <sup>+6</sup> <sub>–6</sub>	142 <sup>+33</sup> <sub>–28</sub>	15 <sup>+4</sup> <sub>–4</sub>	60 <sup>+28</sup> <sub>–21</sub>
–1.7	1 <sup>+1</sup> <sub>–1</sub>	20 <sup>+18</sup> <sub>–20</sub>	14 <sup>+3</sup> <sub>–4</sub>	121 <sup>+59</sup> <sub>–45</sub>	32 <sup>+6</sup> <sub>–6</sub>	76 <sup>+17</sup> <sub>–16</sub>	17 <sup>+4</sup> <sub>–4</sub>	59 <sup>+20</sup> <sub>–18</sub>
–1.5	3 <sup>+2</sup> <sub>–2</sub>	73 <sup>+67</sup> <sub>–41</sub>	28 <sup>+6</sup> <sub>–5</sub>	386 <sup>+154</sup> <sub>–120</sub>	44 <sup>+7</sup> <sub>–6</sub>	162 <sup>+34</sup> <sub>–30</sub>	22 <sup>+4</sup> <sub>–5</sub>	75 <sup>+25</sup> <sub>–23</sub>
–1.3	1 <sup>+1</sup> <sub>–1</sub>	7 <sup>+8</sup> <sub>–7</sub>	12 <sup>+4</sup> <sub>–4</sub>	494 <sup>+284</sup> <sub>–228</sub>	51 <sup>+7</sup> <sub>–8</sub>	201 <sup>+42</sup> <sub>–40</sub>	21 <sup>+5</sup> <sub>–5</sub>	65 <sup>+24</sup> <sub>–19</sub>
–1.1	3 <sup>+2</sup> <sub>–2</sub>	80 <sup>+67</sup> <sub>–50</sub>	52 <sup>+8</sup> <sub>–7</sub>	710 <sup>+200</sup> <sub>–167</sub>	82 <sup>+9</sup> <sub>–9</sub>	462 <sup>+109</sup> <sub>–94</sub>	36 <sup>+7</sup> <sub>–6</sub>	121 <sup>+31</sup> <sub>–23</sub>
–0.9	13 <sup>+4</sup> <sub>–4</sub>	674 <sup>+318</sup> <sub>–241</sub>	62 <sup>+8</sup> <sub>–8</sub>	1132 <sup>+279</sup> <sub>–234</sub>	146 <sup>+14</sup> <sub>–11</sub>	687 <sup>+119</sup> <sub>–87</sub>	44 <sup>+7</sup> <sub>–7</sub>	121 <sup>+36</sup> <sub>–29</sub>
–0.7	11 <sup>+3</sup> <sub>–3</sub>	666 <sup>+339</sup> <sub>–279</sub>	98 <sup>+11</sup> <sub>–9</sub>	2642 <sup>+721</sup> <sub>–507</sub>	178 <sup>+15</sup> <sub>–12</sub>	1438 <sup>+176</sup> <sub>–146</sub>	50 <sup>+7</sup> <sub>–7</sub>	288 <sup>+56</sup> <sub>–47</sub>
–0.5	19 <sup>+4</sup> <sub>–4</sub>	1786 <sup>+683</sup> <sub>–546</sub>	113 <sup>+11</sup> <sub>–11</sub>	3150 <sup>+573</sup> <sub>–478</sub>	146 <sup>+11</sup> <sub>–11</sub>	1356 <sup>+145</sup> <sub>–135</sub>	37 <sup>+6</sup> <sub>–6</sub>	323 <sup>+91</sup> <sub>–76</sub>
–0.3	18 <sup>+4</sup> <sub>–4</sub>	853 <sup>+290</sup> <sub>–250</sub>	117 <sup>+10</sup> <sub>–10</sub>	3724 <sup>+437</sup> <sub>–432</sub>	77 <sup>+8</sup> <sub>–9</sub>	1099 <sup>+164</sup> <sub>–170</sub>	14 <sup>+4</sup> <sub>–4</sub>	81 <sup>+29</sup> <sub>–25</sub>
–0.1	17 <sup>+4</sup> <sub>–4</sub>	1439 <sup>+499</sup> <sub>–465</sub>	71 <sup>+9</sup> <sub>–8</sub>	2977 <sup>+514</sup> <sub>–429</sub>	38 <sup>+6</sup> <sub>–6</sub>	540 <sup>+112</sup> <sub>–107</sub>	3 <sup>+2</sup> <sub>–2</sub>	18 <sup>+18</sup> <sub>–11</sub>
0.1	9 <sup>+3</sup> <sub>–3</sub>	921 <sup>+432</sup> <sub>–377</sub>	26 <sup>+5</sup> <sub>–5</sub>	1663 <sup>+482</sup> <sub>–388</sub>	21 <sup>+5</sup> <sub>–5</sub>	600 <sup>+183</sup> <sub>–155</sub>	2 <sup>+2</sup> <sub>–1</sub>	34 <sup>+29</sup> <sub>–23</sub>
0.3	6 <sup>+2</sup> <sub>–3</sub>	1091 <sup>+529</sup> <sub>–466</sub>	15 <sup>+4</sup> <sub>–4</sub>	1272 <sup>+516</sup> <sub>–417</sub>	2 <sup>+1</sup> <sub>–1</sub>	96 <sup>+93</sup> <sub>–69</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>
0.5	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>	0 <sup>+0</sup> <sub>–0</sub>

Note. — The K-dwarf raw and weighted metallicity distribution function for different ranges of  $|Z|$ . This is for the distances between 1.59 and 1.84 kpc.

Table 9. Vertical Gradients for G and K dwarfs

G dwarfs		K dwarfs	
Weighted	TRILEGAL	Weighted	TRILEGAL
$-0.33^{+0.05}_{-0.04}$	0.25	$-0.31^{+0.05}_{-0.05}$	0.27

Note. — The vertical gradient for G and K dwarfs, adjusted to account for the target-selection biases in SEGUE. These parameters are derived from the G-dwarf sample between distances of 1.59 and 2.29 kpc, and the K-dwarf stars between 1.18 and 1.84 kpc. The listed uncertainties on the slope are derived from our bootstrap analysis. We also list the typical offset in slope, due to the correlated errors in [Fe/H] and distance, labeled as TRILEGAL. This effect will increase the negative slope we detect to larger values by around 0.26 dex/kpc.