# MAPPING THE GALACTIC HALO. VI. SPECTROSCOPIC MEASURES OF LUMINOSITY AND METALLICITY 

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#### Abstract

We present our calibration of spectroscopic measures of luminosity and metallicity for halo giant candidates and give metallicities and distances for our first sample of spectroscopically confirmed giants. These giants have distances ranging from 15 to 83 kpc . As surveys reach farther into the Galaxy's halo with K giant samples, identification of giants becomes more difficult. This is because the numbers of foreground halo K dwarfs rise for $V$ magnitudes of 19-20, typical for halo giants at $\sim 100 \mathrm{kpc}$. Our photometric survey uses the strength of the $\mathrm{Mg} b / \mathrm{H}$ feature near $5170 \AA$ to weed K dwarfs out of the disk and thick disk, but we need spectroscopic measures of the strength of the Са ІІ K, Са І $\lambda 4227$, and $\mathrm{Mg} b / \mathrm{H}$ features to distinguish between the very metal-poor dwarfs and halo giants. Using a full error analysis of our spectroscopic measures, we show why a signal-to-noise ratio of $\sim 15$ pixel $^{-1}$ at Ca I $\lambda 4227$ and $\sim 10$ at Ca II K is needed for reliable luminosity discrimination. We use the $\mathrm{Ca}_{\text {II }} \mathrm{K}$ and $\mathrm{Mg} b$ features to measure metallicity in our halo giants, with typical errors (random plus systematic) of 0.3 dex for $[\mathrm{Fe} / \mathrm{H}]$ values from -0.8 to -3.0 .


Key words: Galaxy: evolution - Galaxy: halo - Galaxy: kinematics and dynamics

## 1. INTRODUCTION

The Galaxy's outer halo is a mostly uncharted region whose stars retain important information about its accretion history. Much of what we know about the halo beyond 30 kpc comes from globular clusters and dwarf spheroidal satellites. However, it is not clear that either object is a good tracer of the field stars of the outer halo. Globular clusters contribute only $1 \%$ to the stellar luminosity of the halo, and we should not expect them to trace the other $99 \%$ reliably, given the rather special conditions under which they are thought to form (McLaughlin \& Pudritz 1996). In addition, both globular cluster and dwarf spheroidal galaxy samples are small, which limits the analyses that can be used to study their properties.

[^0]The long dynamical times in the outer halo ( $\sim 1 \mathrm{Gyr}$ ) allow the signatures of satellite accretion to persist for many gigayears (Johnston, Spergel, \& Hernquist 1995). Tidal features from the Sgr dwarf galaxy have now been found to stretch over more than $90^{\circ}$ of the sky (Mateo, Olszewski, \& Morrison 1998; Majewski et al. 1999; Ivezić et al. 2000; Yanny et al. 2000; Dohm-Palmer et al. 2001); if there are other ongoing or past accretions, they will be relatively easy to detect in the outer halo if sufficient numbers of tracer stars can be found.

Models of satellite accretion (Johnston et al. 1995; Helmi \& White 2001; Harding et al. 2001) show that the velocity signature of an accretion will persist long after the spatial substructure of the tidal stream disappears. Luminous stars such as red giants are particularly suited to tracing the outer halo and searching for such tidal features. This is because it is possible to obtain spectra on $4-8 \mathrm{~m}$ class telescopes for
giants at distances out to 100 kpc and thus measure their velocities and metallicities. Velocities of red giant stars in fields toward the overdensity seen by Ivezić et al. (2000) and Yanny et al. (2000) have confirmed its identity as a tidal stream lost by the Sgr dwarf on a previous passage and revealed intriguing evidence for other "wraps," the most distant of which may have been lost by Sgr much earlier (Dohm-Palmer et al. 2001). The metallicities of these red giants will allow us to measure possible abundance gradients in the Sgr progenitor, since its outer regions will be lost first to tidal forces.

Horizontal-branch stars such as RR Lyrae variables and blue horizontal-branch ( BHB ) stars are easier to find than red giants, and in fact most of the field stars presently known in the outer halo are such stars (Saha 1985; Norris \& Hawkins 1991; Ivezić et al. 2000; Yanny et al. 2000). However, follow-up spectroscopy for horizontalbranch stars is more difficult. Their lower luminosity makes spectroscopic follow-up more time consuming, and in the case of BHB stars spectra are needed to confirm their luminosity (Pier 1983; Norris \& Hawkins 1991; Kinman, Suntzeff, \& Kraft 1994). Also, the high temperatures of BHB stars prohibit accurate metallicity measures unless heroic efforts are made, and the pulsations of the RR Lyrae variables (a typical velocity amplitude is 70 $\mathrm{km} \mathrm{s}^{-1}$, Smith 1995) make velocity measurements complex unless an light curve and a recent ephemeris are available.

It is clear that the discovery of a sizeable sample of red giants in the outer halo will allow much more powerful studies of its structure and origin. In Morrison et al. (2000, 2001) we discuss our photometric search method, which uses a narrowband filter (" 51 "") to measure the strength of the $\mathrm{Mg} b / \mathrm{H}$ feature near $5170 \AA$. This feature is a luminosity discriminant in late-G and K stars. In this paper we discuss the other important part of the search method: spectroscopic confirmation of luminosity. While the photometric survey separates halo giants reliably from disk and thick disk dwarfs, the spectroscopic differences between very metal-poor halo dwarfs and halo giants are more subtle. Spectra with a signal-to-noise ratio $(\mathrm{S} / \mathrm{N}) \sim 15$ pixel $^{-1}$ are needed to separate these.

In § 2 we describe our spectroscopic observations, and in $\S 3$ the standard stars we use to calibrate the measurements, including a newly identified K subdwarf with $[\mathrm{Fe} / \mathrm{H}]=$ -3.2. In $\S 4$ we discuss the synthetic spectra we use to supplement our standards at the metal-poor end, and in $\S 5$ we define the spectroscopic indices used. Section 6 describes the variation of the indices with temperature, $[\mathrm{Fe} / \mathrm{H}]$ and luminosity, and describes the method we use to remove dwarfs from our sample and measure $[\mathrm{Fe} / \mathrm{H}]$ for the giants. Section 7 describes our error analysis. In § 8 we describe our distance measurement for the giants. Section 9 presents our observations of halo giants identified to date, including a likely member of the Sextans dwarf spheroidal galaxy, and § 10 compares our photometric and spectroscopic measures of $[\mathrm{Fe} / \mathrm{H}]$ for these stars.

## 2. OBSERVATIONS

Spectra for halo giant candidates were taken during runs in 1999 May, 2000 January and March on the Kitt Peak National Observatory (KPNO) $4 \mathrm{~m}, 2000$ May on the Cerro Tololo Inter-American Observatory (CTIO) 4 m , and 2001

February on the Magellan I 6.5 m telescope. The Kitt Peak National Observatory (KPNO) 4 m data were taken with the RC spectrograph. The KP007 grating was used, giving a resolution of 3.5 A and a spectroscopic range from 3500 to 5900 A. The CTIO 4 m data were taken with the RC spectrograph and the KPGL1 grating, giving a resolution of 2.8 A and a spectral range of 3500 to 6450 A. The Magellan I data were taken with the $\mathrm{B} \& \mathrm{C}$ spectrograph, a 600 line grating, a resolution of $2.5 \AA$, and a wavelength range from 3850 to 5300 A . All observations were made at the parallactic angle in order to minimize the loss of UV and blue light from the stars.

## 3. SPECTROSCOPIC STANDARDS

The calculation of metallicity and luminosity for our program stars is done by a comparison of the strength of three line indices to the temperature, measured by the $M-T_{2}$ color of the star obtained from our photometric survey. These indices measure the Са II K line, the Са у $\lambda 4227$ line and the $\mathrm{Mg} b / \mathrm{H}$ feature. Examples of spectra illustrating the behavior of these three lines for changing metallicity and luminosity are given in Morrison et al. (2000, 2001).

Since our photometric survey uses the Washington system and, in particular, the $M-T_{2}$ color to measure temperature, it is advantageous to use spectroscopic standard stars with known $M-T_{2}$ colors. In addition, $V-I$ transforms very well to $M-T_{2}$, and so stars with $V-I$ colors are also good standards. Where necessary, we have supplemented our sample with stars which have $b-y$ or $B-V$ colors only. Transformations between these three colors and $M-T_{2}$ are given in the Appendix of Morrison et al. (2000). We choose stars with low reddening values and, if possible, use measurements of reddening from Stromgren photometry of each individual star (available for lowlatitude stars in Anthony-Twarog \& Twarog 1994). Otherwise we use the reddening values of Schlegel, Finkbeiner, \& Davis (1998). For the few stars with such small distances that the full reddening estimate is not applicable, we use the technique of Bond (1980) to estimate the amount of reddening along the line of sight to the star.

### 3.1. Dwarf and Subdwarf Standards

We aim to cover as much of the parameter space of $[\mathrm{Fe} / \mathrm{H}]$ and $\mathrm{M}-T_{2}$ color as possible. This is particularly difficult in the case of K subdwarfs with $[\mathrm{Fe} / \mathrm{H}]<-2.0$, which cannot be distinguished from K giants in our photometric survey. Unfortunately, few such stars are known: the calibrations of Carney \& Latham (1987), Ryan (1989) and others are primarily for F and early-G stars, and barely extend to the blue edge of our color range. There is much recent work on M subdwarfs (for example Monet et al. 1992), but these stars are too red for our purposes.

Figure 1 shows the coverage of $M-T_{2}$ and $[\mathrm{Fe} / \mathrm{H}]$ for our dwarf and subdwarf standards. It should be noted that, below $[\mathrm{Fe} / \mathrm{H}]=-1.5$, the few stars shown represent most of the known K subdwarfs. The most metal-poor one ( $[\mathrm{Fe} / \mathrm{H}]=$ -3.2 ) was identified for this survey. The separation of these poorly studied metal-poor stars from halo K giants in our sample is one of the major tasks of this paper.

Whenever possible, the standard star $[\mathrm{Fe} / \mathrm{H}]$ values come from high- $\mathrm{S} / \mathrm{N}$, high-dispersion spectroscopic studies. In


Fig. 1.-Coverage of $M-T_{2}$ and $[\mathrm{Fe} / \mathrm{H}]$ for our collection of dwarf and subdwarf standards.
the case of some of the nearby dwarf stars, we use the photometric metallicities of Eggen (1998). Values of metallicity, $M-T_{2}$ color, and $E(B-V)$ for our dwarf and subdwarf standards are given in Table 1.

### 3.1.1. The Extremely Metal-poor K Dwarf G160-30

We identified G160-30 as a possible extremely metal-poor dwarf from its red color and large ultraviolet excess (Carney et al. 2001). Its temperature is too low for the Laird, Carney, \& Latham (1988) metallicity calibration, but its spectrum shows that it is very metal-poor (see Fig. 2).

The only photometry available for G160-30 is in the $U B V$ system. To derive estimates of the star's $M-T_{2}$ and effective temperature, we use the color-magnitude diagrams of the metal-poor globular cluster M92 in $V$ versus $B-V$ (Stetson \& Harris 1988) and $V$ versus $V-I$ (Piotto, Cool, \& King 1997) and the synthetic colors of Bessell, Castelli, \& Plez (1998). Since there is little change in color or absolute magnitude with $[\mathrm{Fe} / \mathrm{H}]$ below the metallicity of M92 ( $[\mathrm{Fe} / \mathrm{H}]=-2.2$, Carretta \& Gratton 1997), this cluster is a good choice for deriving color transformations for metalpoor stars. The Schlegel et al. (1998) value of $E(B-V)$ for the direction of G160-30 is 0.11, and G160-30 has $B-V=1.11$ (Carney et al. 2001). Solving iteratively for its distance and reddening using the M92 color-magnitude diagram and the method of Bond (1980), we find that it has a distance of 300 pc and $E(B-V)=0.09$. Using the $V$ magnitude corresponding to $(B-V)_{0}=1.02$ in the colormagnitude diagrams of Stetson \& Harris (1988) and Piotto, Cool, \& King (1997), we derive a $V-I$ color of 1.20 and thus an $M-T_{2}$ color of 1.51 . Both the $B-V$ and $V-I$ colors are consistent with an effective temperature of 4450 K .

Synthetic spectra were calculated with $T_{\text {eff }}=4400$ and $[\mathrm{O} / \mathrm{Fe}]=0.6, \quad[\mathrm{Mg} / \mathrm{Fe}]=[\mathrm{Ca} / \mathrm{Fe}]=0.4$, and $[\mathrm{Fe} / \mathrm{H}]=$ $-2.50,-3.00$, and -3.49 by one of us (J. E. N.). Figure 2 shows the comparison of the actual spectrum of G160-30

TABLE 1
Metallicity and Color of Dwarf Standards

| Star ID | [ $\mathrm{Fe} / \mathrm{H}$ ] | $(b-y)_{0}$ | $(V-I)_{0}$ | $(B-V)_{0}$ | $\left(M-T_{2}\right)_{0}$ | $E(B-V)$ | Source |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |  |  | [Fe/H] | Photometry | $E(B-V)$ |
| HD 25329 | -1.76 | $\ldots$ | ... | $\ldots$ | 1.14 | 0.04 | 9, 11, 12 | 8 | 3 |
| HD46663. | -2.44 | ... | 1.08 | . | 1.34 | 0.01 | 4 | 4 | 4 |
| HD 98281 | -0.25 | 0.46 | ... | . | 1.01 | 0.00 | 7 | 8 | 7 |
| HD $108564{ }^{\text {a }}$ | -1.18 | 0.57 | ... | $\cdots$ | 1.34 | 0.00 | 11 | 7 | 7 |
| HD 117635... | -0.48 | ... | ... | ... | 1.083 | 0.00 | 13 | 8 | 7 |
| HD 134440... | $-1.42^{\text {c }}$ | ... | 0.973 | ... | 1.22 | 0.00 | 11, 12, 14 | 15 | 3 |
| HD 161848.. | -0.18 | $\ldots$ | . | $\ldots$ | 1.12 | 0.00 | 7 | 8 | 7 |
| HD 182488.. | 0.08 | ... | ... | ... | 1.03 | 0.00 | 7 | 8 | 8 |
| HD 190404.. | -0.44 | $\ldots$ | ... | $\ldots$ | 1.11 | 0.00 | 7 | 8 | 8 |
| BD+41 3306 . | -0.62 | ... | 0.93 | ... | 1.18 | 0.00 | 11 | 10 | 2 |
| BD-00 4234 ${ }^{\text {a }}$ | -0.91 | 0.58 | ... | ... | 1.36 | 0.00 | 16 | 17 | 3 |
| G30-52 ${ }^{\text {a }}$. | -2.1 | 0.498 | ... | $\ldots$ | 1.10 | 0.00 | 1 | 2 | 2 |
| G86-39. | -2.00 | 0.522 | $\ldots$ |  | 1.20 | 0.00 | 1 | 2 | 3 |
| G160-30 . | -3.20 | ... | ... | 1.02 | 1.51 | 0.09 | 18 | 2 | $5^{\text {d }}$ |
| G194-37.. | -2.03 | $\ldots$ | ... | 0.80 | 1.20 | 0.03 | 2 | 2 | 2 |
| G202-25.. | -0.38 | $\ldots$ | ... | 0.87 | 1.15: | 0.00 | 2 | 2 | 2 |
| G223-82.. | -0.76 | ... | ... | 0.85 | 1.15: | 0.00 | 2 | 2 | 2 |
| G251-53......... | $-1.87{ }^{\text {b }}$ | $\cdots$ | 1.24 | . . | 1.57 | 0.00 | 6 | 4 | 3 |

[^1]

FIG. 2.-Top: Spectrum of G160-30 observed in 2000 January on the KPNO 4 m , compared with (remaining panels) synthetic spectra calculated for $[\mathrm{Fe} / \mathrm{H}]$-values, ranging from -3.49 to -2.50 . The real spectrum most closely resembles the synthetic one with $[\mathrm{Fe} / \mathrm{H}]=-3.00$.
with these three synthetic spectra. It can be seen that the spectrum most closely resembles the one with $[\mathrm{Fe} / \mathrm{H}]=$ -3.0. To obtain a more accurate measure of $[\mathrm{Fe} / \mathrm{H}]$, the $K^{\prime}$ index of Beers et al. (1999) was calculated from these spectra, and compared with the value of $K^{\prime}$ obtained from our observations of this star on three different observing runs and two telescopes: a mean of $K^{\prime}=6.69$. Interpolating in the $K^{\prime}$-values from the synthetic spectra gives our estimate of $[\mathrm{Fe} / \mathrm{H}]=-3.2$. This is the most metal-poor K dwarf currently known.

### 3.2. Giant Standards

In order to tie our calibration to a consistent metallicity scale, we use globular cluster giants as our primary calibrators. We choose globular clusters with good $M-T_{2}$ or $V-I$ photometry and supplement these with field-star standards when suitable clusters are not accessible, as well as to include some standards with metallicity lower than that of any globular cluster. We use the new metallicity scale of Carretta \& Gratton (1997) for the globular clusters, and in almost all cases we use high-quality high-dispersion analyses for the metallicities of the field giants. The compilation


Fig. 3.-Coverage of $M-T_{2}$ and $[\mathrm{Fe} / \mathrm{H}]$ for our collection of giant standards. Field stars are shown with stars, globular cluster stars with filled circles.
of Beers et al. (1999) was particularly helpful when we were compiling high-quality data for the field giants. Table 2 gives the adopted values of $[\mathrm{Fe} / \mathrm{H}], M-T_{2}$, and $E(B-V)$ for our giant standards, as well as their sources.

Figure 3 shows the range of metallicity and $M-T_{2}$ covered by our giant standards.

All but three of our giant standards are on the first-ascent giant branch. Two (HD 195636 and BD +09 2860) are on the red horizontal branch (and in fact are too blue for our giant color range), while $\mathrm{BD}+521601$ is on the asymptotic giant branch. The evolutionary state of these stars has negligible effect on their derived metallicity and luminosity.

## 4. SYNTHETIC SPECTRA

At the metal-poor end we supplemented our giant calibrator sample using synthetic spectra calculated for $[\mathrm{Fe} / \mathrm{H}]=-3.0$ with the code developed and described by Cottrell \& Norris (1978). The calculations employed the LTE model atmospheric models of Kurucz (1993a), and a line list comprising atomic data provided from a comprehensive compilation of R. A. Bell, together with molecular data for CH and MgH from Kurucz (1993b and 2000), respectively. We note for completeness that for CH the $g f$ values were scaled by 0.35 to force reproduction of the CH band at 4300 A between the Beckers, Bridges, \& Gilliam (1976) solar atlas and the synthetic spectrum for the Kurucz model $\left(T_{\text {eff }} / \log g /[\mathrm{Fe} / \mathrm{H}] / \xi=5780 / 4.44 / 0.00 / 1.0\right)$. For MgH no renormalization was made, based on a satisfactory fit near 5140 A between the Griffin (1968) atlas of Arcturus and the synthetic spectrum for the model 4400/1.8/-0.6/ 1.5 with $[\mathrm{Mg} / \mathrm{Fe}]=0.2$.

In the following sections we shall use synthetic spectra to extend our empirical abundance calibrations to values below $[\mathrm{Fe} / \mathrm{H}]=-2.0$. It is perhaps worth noting that

TABLE 2
Metallicity and Color of Giant Standards

| Star ID | [ $\mathrm{Fe} / \mathrm{H}]$ | $(b-y)_{0}$ | $(V-I)_{0}$ | $(B-V)_{0}$ | $\left(M-T_{2}\right)_{0}$ | $E(B-V)$ | Source |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |  |  | [Fe/H] | Photometry | $E(B-V)$ |
| NGC 1046603 .............................. | -0.70 | $\ldots$ | 0.85 | $\ldots$ | 1.07 | 0.04 | 3 | 11 | 6 |
| NGC 1045640 .............................. | -0.70 | $\ldots$ | 0.95 | $\ldots$ | 1.20 | 0.04 | 3 | 11 | 6 |
| NGC 1045645 .............................. | -0.70 | $\ldots$ | 1.04 | $\ldots$ | 1.31 | 0.04 | 3 | 11 | 6 |
| NGC 1045636 .............................. | -0.70 | $\ldots$ | 1.14 | ... | 1.44 | 0.04 | 3 | 11 | 6 |
| NGC 1851 S315 ............................ | -1.08 | $\cdots$ | 0.81 | ... | 1.02 | 0.02 | 30 | 11 | 6 |
| NGC 1851 S173 ............................ | -1.08 | ... | 0.97 | ... | 1.22 | 0.02 | 30 | 11 | 6 |
| NGC 1851 S293 ............................ | -1.08 | $\ldots$ | 1.04 | ... | 1.31 | 0.02 | 30 | 11 | 6 |
| NGC 459071 ................................ | -1.99 | ... | ... | ... | 1.15 | 0.05 | 3 | 14 | 6 |
| NGC 459073 ................................ | -1.99 | ... | $\ldots$ | $\ldots$ | 1.45 | 0.05 | 3 | 14 | 6 |
| NGC 5053 C ................................. | -2.43 | $\ldots$ | 1.20 | ... | 1.51 | 0.04 | 30 | 8 | 6 |
| NGC 5053 D................................ | -2.43 | ... | 1.13 | $\ldots$ | 1.42 | 0.04 | 30 | 8 | 6 |
| M3 (NGC 5272) Cud 205 (III-28)....... | -1.34 | $\ldots$ | ... | 1.45 | 1.83 | . 01 | 3 | $9,10^{\text {a }}$ | 6 |
| M3 (NGC 5272) Cud 250 (S)............. | -1.34 | $\ldots$ | 0.94 | 1.11 | 1.40 | . 01 | 3 | $9,10^{\text {a }}$ | 6 |
| M3 (NGC 5272) Cud 354 (L)............. | -1.34 | $\ldots$ | 0.82 | 1.00 | 1.26 | . 01 | 3 | $9,10^{\text {a }}$ | 6 |
| M3 (NGC 5272) Cud 1327 (AT)......... | -1.34 | ... | 0.74 | 0.94 | 1.19 | . 01 | 3 | $9,10^{\text {a }}$ | 6 |
| NGC $617116 . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . ~$ | -0.90 | ... | ... | 1.11 | 1.45 | 0.33 | 1,3 | 4 | 6 |
| NGC 617120 ................................ | -0.90 | $\ldots$ | ... | 1.06 | 1.40 | 0.33 | 1,3 | 4,7 | 6 |
| NGC 617162 ................................ | -0.90 | $\ldots$ | $\ldots$ | 1.26 | 1.58 | 0.33 | 1,3 | 4,7 | 6 |
| NGC 639725 ................................ | -1.82 | $\ldots$ | $\ldots$ | ... | 1.20 | 0.18 | 3 | 14 | 6 |
| NGC 639743 ................................ | -1.82 | $\ldots$ | $\ldots$ | $\cdots$ | 1.40 | 0.18 | 3 | 14 | 6 |
| NGC 6397428 .............................. | -1.82 | ... |  | $\ldots$ | 1.31 | 0.18 | 3 | 14 | 6 |
| NGC 6752 A3 ............................... | -1.42 | $\ldots$ | 1.15 | $\ldots$ | 1.45 | 0.04 | 3 | 11 | 6 |
| M2 (NGC 7089) I-2........................ | -1.35 | $\ldots$ | 1.15 | $\ldots$ | 1.45 | 0.06 | 1,3 | 11,12 | 3 |
| M2 (NGC 7089) A ......................... | -1.35 | ... | 1.39 | ... | 1.75 | 0.06 | 1,3 | 11, 12 | 3 |
| M2 (NGC 7089) AC-11 ................... | -1.35 | $\ldots$ | 1.51 | $\ldots$ | 1.90 | 0.06 | 1,3 | 11, 12 | 3 |
|  | -1.21 | 0.52 | ... | $\ldots$ | 1.10 | 0.00 | 15, 18 | 24 | 24 |
| HD 2665 ..................................... | -1.96 | 0.51 | ... | ... | 1.08 | 0.067 | 23 | 24 | 24 |
| HD 6755 ...................................... | -1.57 | $\ldots$ | $\ldots$ | $\ldots$ | 1.04 | 0.03 | 31 | 26 | 27 |
| HD 35179 .................................... | -0.67 | 0.58 | $\ldots$ | $\ldots$ | 1.22 | 0.049 | 20 | 24 | 24 |
| HD 45282 .................................... | -1.35 | 0.451 | ... | ... | 0.90 | 0.02 | 32 | 33 | 33 |
| HD 81192 ..................................... | -0.64 | 0.57 | ... | $\ldots$ | 1.26 | 0.03 | 15 | 25 | $5^{\text {b }}$ |
| HD 81713 .................................... | -0.56 | 0.56 | $\ldots$ | $\cdots$ | 1.21 | 0.05 | 20 | 25 | $5^{\text {b }}$ |
| HD 83212 | -1.47 |  | 1.11 | $\ldots$ | 1.41 | 0.025 | 20 | 29 | 24 |
| HD 103545.................................. | -2.14 | 0.59 | . | . | 1.22 | 0.00 | 31 | 24 | 5 |
| HD 107752................................... | -2.74 | 0.58 | $\ldots$ | $\cdots$ | 1.22 | 0.00 | 15 | 24 | 24 |
| HD 111721................................... | -1.26 | 0.51 | $\ldots$ | $\ldots$ | 1.08 | 0.01 | 17, 19, 20 | 24 | 24 |
| HD 128188................................... | -1.37 | 0.59 | . | - | 1.24 | 0.09 | 20 | 24 | 24 |
| HD 165195.................................... | -2.14 | $\ldots$ | $\cdots$ | $\cdots$ | 1.61 | 0.14 | 17, 18, 19, 22 | 26 | 24 |
| HD 195636................................... | -2.80 | 0.44 | $\cdots$ | $\ldots$ | 0.95 | 0.06 | 15,16 | 24 | 24 |
| HD 199191................................... | -0.70 | ... | ... | ... | 1.11 | 0.10 | 21 | 34 | $5^{\text {b }}$ |
| HD 221170.................................. | -2.12 | .. | $\ldots$ | $\ldots$ | 1.46 | 0.058 | 17, 18, 22 | 26 | 24 |
| BD+52 1601 ................................. | -1.54 | 0.55 | $\cdots$ | $\cdots$ | 1.16 | 0.00 | 15,18 | 2 | 27 |
| BD+09 2574 ................................. | -2.4 | 0.54 | ... | $\ldots$ | 1.14 | 0.00 | 2 | 2 | 27 |
| BD+09 2860 ................................ | $-1.80$ | 0.44 | $\ldots$ | $\ldots$ | 0.95 | 0.00 | 2 | 27 | 27 |
| BD+06648 .................................. | -2.09 |  | $\cdots$ | $\cdots$ | 1.59 | 0.12 | 16, 18, 22 | 28 | 24 |
| BD+05 3098 ................................ | -2.6 | 0.51 | $\ldots$ | $\ldots$ | 1.09 | 0.04 | 2 | 27 | 27 |
| BD+01 2916 ................................ | -1.82 | $\ldots$ | $\cdots$ | $\ldots$ | 1.73 | 0.01 | 18,22 | 28 | 24 |
| GPEC 1834.................................. | -0.99 | $\ldots$ | $\ldots$ | 0.82 | 1.12 | 0.02 | 20 | 20 | 20 |
| GPEC 3672 .................................... | -0.66 | $\cdots$ | $\ldots$ | 0.85 | 1.13 | 0.02 | 20 | 20 | 20 |

${ }^{\text {a }} V-I$ observations obtained using $V$ magnitude from Cudworth 1979 and $V-I$ cluster giant branch from Johnson \& Bolte 1998.
${ }^{\mathrm{b}} E(B-V)$ estimated using Schlegel et al. 1998 reddening and reduction in line-of-sight reddening due to star's distance from Bond 1980.
(1) Zinn 1985; (2) Bond 1980; (3) Carretta \& Gratton 1997; (4) Sandage \& Katem 1964; (5) Schlegel et al. 1998; (6) Harris 1996; (7) Ferraro et al. 1991; (8) Sarajedini \& Milone 1995; (9) Cudworth 1979; (10) Johnson \& Bolte 1998; (11) Da Costa \& Armandroff 1990; (12) Harris 1975; (13) Geisler, Claria, \& Minniti 1997; (14) Geisler, Minniti, \& Claria 1992; (15) Cayrel de Strobel et al. 1997; (16) R. E. Luck 1995, private communication; (17) R. G. Gratton 1998, private communication; (18) Pilachowski, Sneden, \& Kraft 1996; (19) Gratton \& Sneden 1991; (20) Ryan \& Lambert 1995; (21) Cottrell \& Sneden 1986; (22) Shetrone 1996; (23) Fulbright 2000; (24) Anthony-Twarog \& Twarog 1998; (25) Olsen 1993; (26) Harris \& Canterna 1979; (27) Anthony-Twarog \& Twarog 1994; (28) Geisler 1986; (29) Carney 1980; (30) Carretta \& Bragaglia 1998; (31) Burris et al. 2000; (32) Gratton et al. 2000; (33) Hauck \& Mermilliod 1998; (34) Smith 1986.
synthetic spectra have been used extensively to determine carbon abundances from features of CH in extremely metal deficient stars (e.g., Norris, Ryan, \& Beers 2001). We note here that we obtained a good fit of the observed Ca iI K line in the spectrum of the well-known metal-poor giant HD 122563 (data from Norris, Ryan, \& Beers 1996) and the synthetic spectrum having $/ T_{\text {eff }} / \log g /[\mathrm{Fe} / \mathrm{H}] /[\mathrm{Ca} / \mathrm{Fe}] /=/$ 4650/1.5/-2.68/+0.14/ (parameters from Ryan, Norris, \& Beers 1996). Note: No comparisons were made for the Mg feature in metal-poor stars.

## 5. LINE INDICES

Three line indices are defined to measure the strength of the Ca II K line, the $\mathrm{Ca}_{\text {I }} \lambda 4227$ line, and the $\mathrm{Mg} b / \mathrm{H}$ feature, as described in Table 3. The $K^{\prime}$ and $\mathrm{Mg} b / \mathrm{H}$ indices are "pseudo-equivalent widths." These bypass the need for the subjective skill of continuum placement by defining continuum bands on each side of the feature. The mean stellar flux is measured in each of the continuum bands and then interpolated to define the continuum flux at the line. The $K^{\prime}$ index was originally defined by Beers et al. (1999) and uses three different line passbands depending on the strength of the Ca ir K line. We have modified it by moving its blue continuum band to a less crowded region of the spectrum. Our calibration range stretches to cooler stars than that of Beers et al. (1999), making it necessary to define the continuum bands very carefully.

The $\mathrm{Mg}_{1}$ index is based on the index $m(\mathrm{Mg})$ defined by Suntzeff et al. (1986) but is calculated as a pseudoequivalent width. The $\mathrm{Mg}_{2}$ index is calculated in the same way, but it has a modified red continuum band to cope with the smaller wavelength coverage of the Magellan spectrograph. We find no measurable difference between the two Mg indices for stars in common between runs and will refer to both simply as Mg hereafter.

Because the Ca i $\lambda 4227$ line has the $G$ band on one side and the blue CN band on the other, it is difficult to find good continuum bands. We choose to use one nearby continuum band only, and calculate the Ca I index in a similar way to the $S(3839)$ index of Smith \& Norris (1983):

$$
\mathrm{Ca} \mathrm{I}=-2.5 \log \int_{4221.7}^{4231.7} I_{\lambda} d \lambda / \int_{4240}^{4247} I_{\lambda} d \lambda
$$

In all cases, the stellar spectra are shifted to rest wavelength before calculating the line indices.

### 5.1. How Well Do the Indices Repeat?

Because we use our spectra to measure velocity as well as metallicity and luminosity, we need a narrower slit width

TABLE 3
Passbands for Spectral Indices

| Index | Line Band | Blue Sideband | Red Sideband |
| :---: | :---: | :---: | :---: |
| $K^{\prime}(\mathrm{K} 6) \ldots \ldots \ldots .$. | $3930.7-3936.7$ | $3908-3918$ | $4010-4025$ |
| $K^{\prime}(\mathrm{K} 12) \ldots \ldots \ldots$. | $3927.7-3939.7$ | $3908-3918$ | $4010-4025$ |
| $K^{\prime}(\mathrm{K} 18) \ldots \ldots \ldots$. | $3924.7-3942.7$ | $3908-3918$ | $4010-4025$ |
| $\mathrm{Ca} \boldsymbol{\mathrm { I }} \ldots \ldots \ldots \ldots \ldots$. | $4221.7-4231.7$ | $\ldots$ | $4240-4247$ |
| $\mathrm{Mg}_{1} \ldots \ldots \ldots \ldots \ldots$. | $5130-5200$ | $4935-4975$ | $5303-5367$ |
| $\mathrm{Mg}_{2} \ldots \ldots \ldots \ldots \ldots$. | $5130-5200$ | $4935-4975$ | $5217-5258$ |

than used for spectrophotometric observations, so we cannot flux-calibrate our spectra. We find, however, that if spectra are taken at the parallactic angle with sufficient $\mathrm{S} / \mathrm{N}$, values of line indices agree well from run to run on the same telescope and instrument combination. The Mg and Ca i $\lambda 4227$ indices also agree well between telescopes, but the $K^{\prime}$ index agrees less well in this case. While the pseudoequivalent width measurements will be independent of the slope of the stellar continuum, because they are obtained by linearly interpolating between the continuum bands, higher order differences in continuum shape will not be compensated for. This is likely to be the cause of some of the disagreement between $K^{\prime}$ values for different telescopes.

In order to make a correction for the different continuum shapes (caused mostly by the spectrograph and detector response), a very metal-poor star with color close to the blue end of our calibration $\left(M-T_{2}=1.10\right)$ is chosen for each run. The reasonably featureless spectrum of this star is fitted with a smooth function, which preserves the shape of the spectrum but removes the spectral lines. This is done with the IRAF task FIT1D, using a cubic spline of order 5-7. All spectra are divided by this smooth function before measuring indices. After this procedure, there are no run-to-run differences seen in the $\mathrm{Ca} \mathrm{I}, \mathrm{Mg}_{1}$, and $\mathrm{Mg}_{2}$ indices, but there are still small differences in $K^{\prime}$ values from run to run, as can be seen in Figure 4, which shows the difference between the $K^{\prime}$ value measured on each run and the average over all runs. These plots are used to derive small zero-point corrections for the $K^{\prime}$ values for each run.


Fig. 4.-Deviations from average $K^{\prime}$-value calculated over all runs, for observations on the KPNO 4 m (top), the CTIO 4 m (middle), and the Magellan I 6.5 m (bottom).

## 6. METALLICITY AND LUMINOSITY CALIBRATION

We use our spectroscopic observations of globular cluster giants to define our metallicity calibration. These have the advantage of being on a consistent metallicity scale and giving a number of stars with exactly the same metallicity over a range of temperature in each cluster. We then use observations of field giants to test the accuracy of our metallicity calibration.

The different indices are used as follows: Ca iI K has little dependence on luminosity so it is our first metallicity indicator. Ca I $\lambda 4227$ and the $\mathrm{Mg} b / \mathrm{H}$ features are sensitive to both luminosity and metallicity and so are used first for luminosity discrimination. Most dwarf stars can be eliminated solely via their strong Ca I and $\mathrm{Mg} b / \mathrm{H}$ features for their $M-T_{2}$ color, while halo dwarfs are eliminated by comparing the Ca II index with Ca I and Mg indices. $K^{\prime}$ is a good metallicity indicator for low-metallicity giants $([\mathrm{Fe} / \mathrm{H}]<-1.0) . \mathrm{Mg}$ is good for higher metallicity giants ( $[\mathrm{Fe} / \mathrm{H}]>-1.5$ ).

The strategy that we follow here is to derive metallicity calibrations for all three indices, using globular cluster giants only. Then we will show that applying these calibrations to dwarf stars produces consistent results for $K^{\prime}$ but very discrepant results for the Ca I and Mg indices, because dwarf stars have stronger Ca I and Mg features for a given metallicity than giants. We use these discrepant results to indicate that the star is a dwarf.

Tables 4 and 5 give values of the three indices for our dwarf and giant calibrators, respectively. These values have been corrected for run-to-run differences, as described in the previous section, and averaged when the star was observed on more than one occasion. Note that the figures plot multiple observations of the same star as separate symbols to show the amount of scatter that occurs for even high-S/N observations.

Figures 5 to 7 show the index values versus $M-T_{2}$ for the globular cluster giants used to define this calibration, the dwarf standards, and the calibration lines adopted. Because of the giant branch luminosity function, the majority of our giant candidates have $M-T_{2}$-values close to 1.10. Although the Washington photometric metallicity calibration reaches

TABLE 4
Spectral Indices for Dwarf Standards

| Star ID | $[\mathrm{Fe} / \mathrm{H}]$ | $\left(M-T_{2}\right)_{0}$ | $K^{\prime}$ | Ca I | Mg |
| :---: | :---: | :---: | ---: | ---: | ---: |
| HD 25329 ....... | -1.76 | 1.14 | 10.50 | -0.10 | 10.10 |
| HD 46663 ....... | -2.44 | 1.34 | 9.35 | -0.04 | 12.33 |
| HD 98281 $\ldots \ldots .$. | -0.25 | 1.01 | 9.84 | -0.20 | 8.15 |
| HD 108564...... | -1.18 | 1.34 | 10.69 | 0.19 | 18.67 |
| HD 117635...... | -0.48 | 1.08 | 9.84 | -0.15 | 10.82 |
| HD 134440...... | -1.42 | 1.22 | 10.79 | -0.07 | 9.44 |
| HD 161848...... | -0.18 | 1.12 | 10.32 | -0.07 | 12.90 |
| HD 182488...... | +0.08 | 1.03 | 9.85 | -0.15 | 10.70 |
| HD 190404...... | -0.44 | 1.11 | 10.54 | -0.05 | 13.30 |
| BD -00 4234.... | -0.91 | 1.36 | 7.86 | -0.01 | 15.60 |
| G30-52 $\ldots \ldots \ldots \ldots .$. | -2.10 | 1.10 | 7.82 | -0.18 | 9.10 |
| G86-39.......... | -2.00 | 1.20 | 10.80 | -0.04 | 11.55 |
| G160-30 $\ldots \ldots \ldots .$. | -3.20 | 1.51 | 6.69 | -0.29 | 3.32 |
| G194-37......... | -2.03 | 1.20 | 10.06 | -0.18 | 6.80 |
| G202-25 $\ldots \ldots \ldots .$. | -0.38 | $1.15:$ | 10.68 | 0.02 | 16.00 |
| G223-82 $\ldots \ldots \ldots .$. | -0.76 | $1.15:$ | 10.86 | 0.03 | 15.40 |
| G251-53 $\ldots \ldots \ldots .$. | -1.87 | 1.57 | 8.47 | -0.10 | 8.95 |

to $M-T_{2}=1.80$, we have chosen only to define the spectroscopic calibration for the region $M-T_{2}=1.10$ to 1.60 , and in fact the great majority of our candidates have colors between 1.10 and 1.40.

Figure 5 shows that $K^{\prime}$ is a very good metallicity indicator for extremely metal-poor giants with $[\mathrm{Fe} / \mathrm{H}]<-1.5$. While it keeps some metallicity sensitivity up to $[\mathrm{Fe} / \mathrm{H}]=-1.0$, the isoabundance lines become closer, meaning that a greater accuracy in measuring the $K^{\prime}$ index is needed to achieve the same accuracy in $[\mathrm{Fe} / \mathrm{H}]$. This is illustrated by the two most metal-rich clusters used, at $[\mathrm{Fe} / \mathrm{H}]=-0.7$ and -1.08 . These data were taken on the 6.5 m Magellan I telescope, where it is possible to observe relatively faint globular cluster giants with short exposures, and so the data have uniformly high $\mathrm{S} / \mathrm{N}$. In contrast, the data for $[\mathrm{Fe} / \mathrm{H}]=-1.35$ were obtained on the KPNO 4 m where significantly longer exposures are needed for the cluster giants, and there is more scatter about the mean line.

The most difficult region for this indicator is for cool, relatively metal-rich stars such as the two M3 $([\mathrm{Fe} / \mathrm{H}]=$ -1.35 ) giants with $M-T_{2}>1.7$ shown in Figure 5: it can be seen that the $K^{\prime}$ index has begun to saturate. However, since


Fig. 5.-Behavior of the $K^{\prime}$ index with metallicity, temperature, and luminosity. The bottom panel shows the globular cluster giants used to define the metallicity calibration for $K^{\prime}$ : (stars) 47 Tucanae $([\mathrm{Fe} / \mathrm{H}]=$ -0.7); (open triangles) NGC 1851 ( $[\mathrm{Fe} / \mathrm{H}]=-1.08$ ); (closed squares) M2 and M3 $([\mathrm{Fe} / \mathrm{H}]=-1.35)$; (open squares) $\mathrm{NGC} 6397([\mathrm{Fe} / \mathrm{H}]=-1.82)$; (closed circles) NGC $4590([\mathrm{Fe} / \mathrm{H}]=-1.99)$. The lines show the calibration adopted for each of these metallicities, plus the line computed from synthetic spectra for $[\mathrm{Fe} / \mathrm{H}]=-3.0$. The top panel shows the calibration lines derived from the giants, with all our dwarf stars plotted. To first order, the dwarfs occupy the same region on this diagram as the giants: $K^{\prime}$ does not have a strong luminosity sensitivity.

TABLE 5
Spectroscopic Indices for Giant Standards

|  |  |  |
| :--- | :--- | :--- | :--- | ---: | :--- | ---: |

very few of our giant candidates have $M-T_{2}$ greater than 1.4, this is not a large concern.

Because we have chosen to use globular cluster giants to calibrate the metallicity measurement, and approximately half the standards observed were field stars, we can assess the accuracy of the metallicity measurement using these other standard stars. Figure 8 plots the difference between the actual $[\mathrm{Fe} / \mathrm{H}]$ of each standard and the $[\mathrm{Fe} / \mathrm{H}]$ found using the calibration, for the three indices.
The saturation of the $K^{\prime}$ index for high metallicities is seen in the increased scatter in the residuals for $[\mathrm{Fe} / \mathrm{H}]>-1.0$. There also seems to be an offset of a few tenths of a dex between the globular cluster metallicity scale used for 47 Tucanae $([\mathrm{Fe} / \mathrm{H}]=-0.7)$ and the metallicity scale for the field stars with $[\mathrm{Fe} / \mathrm{H}]>-1.0$. We have chosen to stay on
the globular cluster scale here; as we expect few of our halo giants to have metallicities this high, this point is not critical. Restricting the sample to those giants with $M-T_{2}$ between 1.1 and 1.6 and $[\mathrm{Fe} / \mathrm{H}]<-1.0$, we find a mean value $[\mathrm{Fe} / \mathrm{H}]_{K}-[\mathrm{Fe} / \mathrm{H}]_{\text {std }}=0.09$ dex, and a $\sigma$ of 0.2 dex. We thus estimate the $[\mathrm{Fe} / \mathrm{H}]$ calibration error for $K^{\prime}$ to be 0.2 dex.
The middle panel of Figure 8 shows that the Ca I index has a larger scatter for all values of $[\mathrm{Fe} / \mathrm{H}]$. This is likely due to the narrow line and continuum bands used for this index. We will use the Ca I index for luminosity discrimination only, where differences between dwarfs and giants are less subtle (see $\S 6.1$ below).
The bottom panel of Figure 8 shows that the Mg index is more reliable for the higher metallicity standards, although the offset between the derived metallicities of field stars and


Fig. 6.-Behavior of the Ca I $\lambda 4227$ index with metallicity, luminosity, and temperature. Globular cluster giants and adopted calibration lines are shown with symbols as in Fig. 5. Dwarf stars are plotted on the same diagram with crosses: almost all the dwarfs have much stronger Ca I than the globular cluster giants. The two dwarfs which overlap the giant region have $[\mathrm{Fe} / \mathrm{H}]=-1.87$ and -3.2 . Note that this index does not exhibit the saturation effects at cool temperatures which are seen with the $K^{\prime}$ index. The strong temperature sensitivity of this index can be seen in the slope of the 47 Tuc line.

47 Tucanae seen in the top panel is still evident here at a lower level. Restricting the sample to those giants with $M-T_{2}$ between 1.1 and 1.6 and $[\mathrm{Fe} / \mathrm{H}]>-1.5$, we find a mean value $[\mathrm{Fe} / \mathrm{H}]_{\mathrm{Mg}}-[\mathrm{Fe} / \mathrm{H}]_{\text {std }}=0.00$ dex, and a $\sigma$ of 0.25 dex. Our $[\mathrm{Fe} / \mathrm{H}]$ calibration error for Mg is thus 0.25 dex.

To obtain the most accurate metallicity measurement, we average the metallicities obtained from the Ca II K and Mg indices in the $[\mathrm{Fe} / \mathrm{H}]$ range where both indices give good measurements: $[\mathrm{Fe} / \mathrm{H}]$ between -1.0 and -1.5 . For metallicities higher than -1.0 , we use the Mg index only, and for metallicities less than -1.5 we use the $K^{\prime}$ index only.

Occasionally we find that the Mg and $K^{\prime}$ indices disagree significantly, either due to undetected errors such as inconveniently placed cosmic rays or due to real variations in $[\mathrm{Ca} / \mathrm{Mg}]$ in the star. We increase our error estimate to 0.5 dex in order to flag this problem.

### 6.1. Luminosity Calibration

Our method of luminosity discrimination is based on the strength of the Ca I $\lambda 4227$ line and the $\mathrm{Mg} b / \mathrm{H}$ feature: both of these are stronger in dwarfs and subdwarfs than in giants at a given temperature and metallicity (Morrison et al. 2000, 2001). Since these papers were published, we have obtained


Fig. 7.-Behavior of the Mg index with metallicity, luminosity, and temperature, as for Ca I in Fig. 6. Open stars are giants from NGC 6171 $([\mathrm{Fe} / \mathrm{H}]=-0.9)$. The globular cluster calibration lines have been derived by averaging the values for the two globular clusters whose metallicity is close to the marked value. As for the Ca index, all but two very metal-poor dwarfs have stronger Mg features than all the globular cluster stars. Note that the Mg index does not show saturation effects for cool giants, which makes it more suitable for measuring metallicity for more metal-rich stars.
a larger sample of subdwarfs and improved the color and metallicity estimates for several of them.

In Figures 6 and 7 we show the position of the dwarf and subdwarf standards with respect to the calibration lines derived from the giants. The stronger features of the dwarfs are clearly seen. There is a large separation between the giant calibration lines and almost all the dwarfs and subdwarfs in both Ca and Mg ; the two subdwarfs that intersect the giant calibration lines are $\mathrm{G} 251-53([\mathrm{Fe} / \mathrm{H}]=-1.87)$, which intersects the $[\mathrm{Fe} / \mathrm{H}]=-0.7$ line, and $\mathrm{G} 160-30$ $([\mathrm{Fe} / \mathrm{H}]=-3.2)$, which appears between the $[\mathrm{Fe} / \mathrm{H}]=$ -1.08 and $[\mathrm{Fe} / \mathrm{H}]=-1.99$ lines. Even these extreme subdwarfs have strong Ca I and Mg features compared with a giant with the same metallicity.

The best method we have found to measure luminosity is to compare the metallicity derived from the Ca iI K line (which is not sensitive to gravity) to the metallicities derived from the Ca I $\lambda 4227$ line and the $\mathrm{Mg} b / \mathrm{H}$ feature (which are sensitive to gravity). Since our metallicity calibration is derived for giants, the dwarfs will show an unusually high metallicity on the two gravity-sensitive indices, and a reasonably accurate measurement from the $K^{\prime}$ index. Figure 9 illustrates our method.

In the case of relatively metal-rich dwarfs, however, the Mg and Ca I features are so strong that it is not necessary to


FIG. 8.-Residuals between $[\mathrm{Fe} / \mathrm{H}]$ measured using each of the three indices and the actual metallicity of the star, for (top) the $K^{\prime}$ index; (middle) the Ca I index and (bottom) the Mg index. Only standards with $M-T_{2}$ between 1.1 to 1.6 are plotted. Open circles are the globular cluster giants that were used to define the metallicity calibration for this index; closed circles are stars (usually from the field) observed as standards but not used in setting up the calibration.
make this test. If a star has a (giant-calibrated) metallicity from Mg and Ca I , which is solar or above, it is far more likely to be a foreground dwarf than a solar metallicity giant, which would be tens of kiloparsecs away at these magnitudes and thus in the halo where such metallicities are extremely rare. Because our giant candidates are red stars, it takes more time to obtain a spectrum that is well-exposed at Са Іі K , and, if we find strong Mg and Ca I features, we do not need to spend the extra telescope time to confirm its luminosity status. The more metal-poor subdwarfs, however, need the sensitive test using the Ca i and Ca ir lines.

There is one complication when comparing the strength of the Mg features with the Ca II K line strength: some stars have significant variations in these elemental abundance ratios, i.e., $[\mathrm{Mg} / \mathrm{Ca}] \neq 0$. An example is the subdwarf HD 134440 , whose $[\mathrm{Mg} / \mathrm{Ca}]=-0.33$ (King 1997). ${ }^{2}$ This means

[^2]

Fig. 9.-Luminosity-calibration diagram. Since $K^{\prime}$ has little gravity sensitivity and Ca I and Mg have much more, if we subtract the metallicity derived from $K^{\prime}$ from the metallicities derived from the other two indices, we find that dwarfs and giants occupy different regions in this plot. Giants are plotted as filled circles, and dwarfs as crosses. The $K^{\prime}$ index loses sensitivity for high metallicities, but the separation between dwarfs and giants is large at this metallicity. The dwarf with $[\mathrm{Fe} / \mathrm{H}]=-1.42$ and an anomalously low value of $[\mathrm{Fe} / \mathrm{H}]_{\mathrm{Mg}}-[\mathrm{Fe} / \mathrm{H}]_{\mathrm{K}}$ is HD 134440 , which has an unusual pattern of $\alpha$-elements with $[\mathrm{Mg} / \mathrm{Ca}]=-0.33$ (see Table 1 notes). The giants with $[\mathrm{Fe} / \mathrm{H}]=-1.34$ that are close to the dividing line between giants and dwarfs belong to the globular cluster M3, which has only photographic $B-V$ colors available, limiting the accuracy of derived metallicities. M3 is no longer used as a spectroscopic standard for this project for this reason.
that the Ca i $\lambda 4227$ versus Ca II $K$ test is more reliable, since it does not depend on the unknown $[\mathrm{Mg} / \mathrm{Ca}$ ] abundance ratio of the program star. The accuracy of this comparison is largely determined by the $\mathrm{S} / \mathrm{N}$ of these red stars at the Са it K line. Unfortunately, there are no useful $\mathrm{Mg}_{\text {it }}$ lines in the visible region on which to base a similar test using $\mathrm{Mg}_{\mathrm{I}}$ and $\mathrm{Mg}_{\text {II }}$ lines, so we are forced to obtain sufficient $\mathrm{S} / \mathrm{N}$ in the blue for the Ca I/ Ca II comparison.

### 6.1.1. Luminosity Discrimination at $[\mathrm{Fe} / \mathrm{H}]=-3.0$

Since we only have one (quite cool) subdwarf standard with $[\mathrm{Fe} / \mathrm{H}] \leq-3.0$, we use the synthetic spectra to guide our luminosity discrimination for very metal-poor stars. It can be seen in Figure 10 that, while both Mg and Ca i indices show luminosity differences at $[\mathrm{Fe} / \mathrm{H}]=-3.0$ for the red end of our color range, the Mg and Ca I features show only a small variation with luminosity at the blue end.
We used the simulations described in the next section to determine the $\mathrm{S} / \mathrm{N}$ requirements for luminosity discrimination at these very low metallicities. At $M-T_{2}=1.1$, the difference between the synthetic dwarf and giant $\mathbf{M g}$ index values is 0.55 , and Ca I index values 0.03 . The $\sigma$ of the distribution of Mg index values at $\mathrm{S} / \mathrm{N}=20$ pixel $^{-1}$ is 0.033 , and the $\sigma$ for Ca I index values is 0.063 . Thus, $\mathrm{S} / \mathrm{N}$ of $\sim 20$ is required to make a $1 \sigma$ separation between dwarfs and giants at this metallicity. The separation between dwarf and giant lines approximately doubles between $M-T_{2}=1.1$


FIg. 10.-Luminosity sensitivity of Ca and Mg indices as a function of color at $[\mathrm{Fe} / \mathrm{H}]=-3.0$.
and 1.2 , so $\mathrm{S} / \mathrm{N}$ of 20 spectra will give a $2 \sigma$ separation at $M-T_{2}=1.2$. We increase our exposure times accordingly for very weak lined stars.

## 7. ERRORS

In $\S 6$ we estimate the systematic error of our metallicity calibration by examining the scatter of the derived $[\mathrm{Fe} / \mathrm{H}]$ from the true $[\mathrm{Fe} / \mathrm{H}]$ for our standard stars. Contributions to this error will include errors in measurement of $[\mathrm{Fe} / \mathrm{H}]$ for the standards, offsets between metallicity scales for globular clusters and field stars, and measurement errors of the indices for our standard stars. An additional systematic error is caused by extrapolation errors into the regions of parameter space where we have no calibrators (for example, we currently have no red giant standards with $[\mathrm{Fe} / \mathrm{H}]=-3.0$ or below).

The values of the indices for a given star vary from run to run and telescope to telescope, as a result of systematic effects such as continuum shape, which remain after the "flattening" procedure described above, and random effects due to photon statistics and other noise in the spectra. In most cases, since the spectra of the standards were obtained with very high $\mathrm{S} / \mathrm{N}$ (1000 photons or more per pixel), random errors are not an important effect for standards. However, the program stars are significantly fainter. We aim for a S/N of $\sim 15$ per pixel at the Ca I $\lambda 4227$ line for our program stars, although in some cases weather or seeing prevent us from obtaining this. In this section we will investigate the effects of random errors on the measurement of the spectral indices and thus on metallicity and luminosity.

We take a well-exposed giant spectrum of moderate color and metal deficiency (M3 Cud 250, $[\mathrm{Fe} / \mathrm{H}]=-1.34$ ) and degrade it to different $\mathrm{S} / \mathrm{N}$ to illustrate the effect of photon statistics on our measurement errors. (Note that in general the error will depend on the color and metallicity of the star as well as the $\mathrm{S} / \mathrm{N}$ of its spectrum. We give a full error treatment below which takes this into account.)


Fig. 11.-Metallicity values derived from the spectrum of M3 Cud 250 $([\mathrm{Fe} / \mathrm{H}]=-1.34)$ and the $K^{\prime}$ index when the spectrum was degraded to different $\mathrm{S} / \mathrm{N}$.

The spectrum is degraded by adding Gaussian noise corresponding to $\mathrm{S} / \mathrm{N}$ from 5 to 50 pixel $^{-1}$; for each noise level we add random noise 1000 times. Then we calculate all three spectral indices and use the calibrations of $\S 6$ to derive the metallicity from each error-degraded spectrum. Figure 11


FIG. 12.-Histogram of $[\mathrm{Fe} / \mathrm{H}]$-values obtained from the $K^{\prime}$ index when the M3 Cud 250 spectrum was degraded to a $\mathrm{S} / \mathrm{N}$ of 5 (top), 10 (middle), and 15 (bottom).


Fig. 13.-Histogram of $[\mathrm{Fe} / \mathrm{H}]$-values obtained from the Ca I $\lambda 4227$ index when the M3 Cud 250 spectrum was degraded to a $\mathrm{S} / \mathrm{N}$ of 5 (top), 10 (middle), and 15 (bottom).


Fig. 14.-Histogram of $[\mathrm{Fe} / \mathrm{H}]$-values obtained from the Mg index when the M3 Cud 250 spectrum was degraded to a $\mathrm{S} / \mathrm{N}$ of 5 (top), 10 (middle), and 15 (bottom).
shows the behavior of $[\mathrm{Fe} / \mathrm{H}]$ derived from the $K^{\prime}$ index for this star as a function of $\mathrm{S} / \mathrm{N}$.

It is clear from this figure that large errors in metallicity will result from low $\mathrm{S} / \mathrm{N}$ spectra $(\mathrm{S} / \mathrm{N}<10)$. More detail of the error distributions can be seen in Figures 12, 13, and 14, which show the histograms of $[\mathrm{Fe} / \mathrm{H}]$ derived from 1000 error-degraded spectra with $\mathrm{S} / \mathrm{N}$ of 5,10 , and 15 pixel $^{-1}$. All three error histograms show a marked low-metallicity tail but little extension toward high metallicity. This is because the metallicity calibration lines become closer together for higher metallicity and is very useful in the luminosity calibration, since few genuine giants have CaI and Mg features as strong as disk and thick disk dwarfs.

In summary, a $\mathrm{S} / \mathrm{N}$ of $10-15$ pixel $^{-1}$ is needed in order to measure $[\mathrm{Fe} / \mathrm{H}]$ to a photon-statistic accuracy of $0.2-0.3$ dex using the $K^{\prime}$ and Mg indices; the Ca I $\lambda 4227$ index is much less accurate, showing a $\sigma$ of 0.65 dex for $\mathrm{S} / \mathrm{N}=15$.

How does the $\mathrm{S} / \mathrm{N}$ of the spectrum affect the accuracy of the luminosity calibration? We made similar simulations to those described above, degrading the high-S/N spectrum of the subdwarf HD 25329 to $\mathrm{S} / \mathrm{N}$ values ranging from 5 to 50 . Figure 15 shows the reason why we aim for a $S / N$ of $\sim 15$ at the Ca I line in our spectra: for this $\mathrm{S} / \mathrm{N}$ the error distributions of the M3 giant and the subdwarf do not overlap.

### 7.1. Complete Error Calculation

In general, when calculating metallicity errors for a program star, we need to take its color and metallicity into account as well as the $\mathrm{S} / \mathrm{N}$ of its spectrum. This is because the metallicity calibration lines of Figures 5 to 7 are not equally spaced, and, where they are closer together, a higher $\mathrm{S} / \mathrm{N}$ is needed to get the same accuracy. For example, at the blue end of our calibration, the sensitivity of the Ca I and Mg indices is dropping, and so the isoabundance lines lie closer together and a given error in an index value will lead to a larger metallicity error than for a redder star.

We calculate the random errors on metallicity for the program stars by a combination of analytic calculation and Monte Carlo simulations. Since all three indices are ratios of averaged pixel counts over the line and continuum bands, we begin by calculating the errors on the averaged pixel


Fig. 15.-Histogram of $[\mathrm{Fe} / \mathrm{H}]$-values obtained from the Ca index for M3 Cud 250 spectrum (unshaded) and the subdwarf HD 25329 spectrum (shaded) when both were was degraded to a $\mathrm{S} / \mathrm{N}$ of 15 .

| $l$ | $b$ | $M_{0}$ | $\left(M-T_{2}\right)_{0}$ | Error | $(C-M)_{0}$ | Error | $(M-51)_{0}$ | $[\mathrm{Fe} / \mathrm{H}]_{\mathrm{K}}$ | Error | $[\mathrm{Fe} / \mathrm{H}]_{\mathrm{Ca} ~}$ | Error | $[\mathrm{Fe} / \mathrm{H}]_{\mathrm{Mg}}$ | Error | Lum. | Run |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 3.059 ............... | 61.296 | 19.44 | 1.17 | 0.015 | 0.75 | 0.016 | 0.00 | -1.47 | 0.31 | -0.74 | 1.80 | -1.27 | 0.37 | r | 1999 May |
| 3.789 ................ | 61.097 | 16.55 | 1.17 | 0.027 | 0.74 | 0.009 | 0.00 | -1.19 | 0.23 | -0.46 | 0.46 | -0.37 | 0.22 | r | 1999 May |
| 11.376 .............. | 51.753 | 18.17 | 1.29 | 0.010 | 0.89 | 0.010 | -0.07 | -1.75 | 0.07 | -0.08 | 0.09 | 0.11 | 0.03 | S | 1999 May |
| 11.853 .............. | 51.950 | 17.81 | 1.19 | 0.013 | 0.95 | 0.010 | 0.00 | -0.79 | 0.40 | -1.89 | 1.75 | -1.06 | 0.10 | g | 1999 May |
| 17.038 .............. | 46.397 | 17.02 | 1.12 | 0.016 | 0.70 | 0.012 | 0.03 | -1.75 | 0.29 | -0.72 | 0.96 | -1.48 | 0.16 | s | 2000 May |
| 17.139 .............. | 46.780 | 18.43 | 1.23 | 0.008 | 0.93 | 0.011 | 0.04 | -1.91 | 0.07 | -0.79 | 0.08 | -1.19 | 0.03 | s | 1999 May |
| 17.353 .............. | 46.505 | 16.76 | 1.23 | 0.011 | 0.85 | 0.009 | 0.06 | -1.14 | 0.25 | -0.90 | 0.56 | -1.22 | 0.09 | g | 1999 May |
| 17.489 .............. | 46.781 | 18.69 | 1.30 | 0.011 | 0.89 | 0.015 | -0.01 | -0.57 | 0.83 | -0.06 | 0.36 | 0.22 | 0.14 |  | 1999 May |
| 218.354 | 37.755 | 17.02 | 1.27 | 0.028 | 0.90 | 0.021 | 0.01 | -1.54 | 0.04 | -1.00 | 0.06 | -0.87 | 0.03 | r | 2000 Mar |
| 222.967 | 43.511 | 18.48 | 1.09 | 0.015 | 0.54 | 0.016 | 0.04 | -2.50 | 0.31 | -4.05 | 5.00 | -1.94 | 1.07 | r | 2000 Mar |
| 223.232 ............ | 43.577 | 18.17 | 1.13 | 0.019 | 0.74 | 0.020 | 0.02 | -1.20 | 0.07 | -0.40 | 0.18 | -0.17 | 0.21 | S | 2000 Mar |
| 223.422 ............ | 42.925 | 17.52 | 1.32 | 0.020 | 0.98 | 0.021 | -0.06 | -1.39 | 0.52 | -0.47 | 0.47 | 0.31 | 0.14 | S | 1999 May |
| 223.446 ............ | 43.439 | 17.01 | 1.38 | 0.030 | 1.10 | 0.019 | 0.03 | -1.26 | 0.13 | -1.06 | 0.30 | -1.09 | 0.06 | g | 2000 Jan |
| 223.454 | 42.974 | 16.72 | 1.12 | 0.026 | 0.61 | 0.023 | 0.02 | -2.45 | 0.12 | -1.45 | 1.74 | -2.10 | 0.34 | r | 2000 Mar |
| 232.256 ............ | 24.597 | 16.92 | 1.14 | 0.038 | 0.75 | 0.020 | -0.01 | -0.88 | 0.51 | 1.04 | 0.83 | -0.35 | 0.34 | s | 2000 May |
| 232.462 ............ | 24.393 | 17.52 | 1.31 | 0.009 | 1.06 | 0.009 | 0.02 | -2.02 | 0.30 | -1.03 | 1.83 | -0.19 | 0.14 | d | 2000 Mar |
| 232.526 | 24.916 | 18.05 | 1.10 | 0.018 | 0.70 | 0.015 | 0.02 | -1.01 | 0.21 | -0.62 | 1.02 | -0.70 | 0.22 | g | 2000 Jan |
| 233.896 ............ | 32.321 | 18.10 | 1.11 | 0.007 | 0.68 | 0.009 | 0.02 | -1.04 | 0.25 | -2.22 | 1.86 | -1.06 | 0.15 | g |  |
| "..................... | " | 18.10 | 1.11 | 0.007 | 0.68 | 0.009 | 0.02 | -1.03 | 0.26 | -3.12 | 2.39 | -1.01 | 0.23 | g | 2000 Jan |
| "..................... | " | 18.10 | 1.11 | 0.007 | 0.68 | 0.009 | 0.02 | -1.15 | 0.83 | -0.84 | 2.97 | -1.10 | 0.19 |  | 2000 May |
| 233.995 ............ | 31.771 | 19.18 | 1.14 | 0.010 | 0.71 | 0.009 | 0.00 | -0.86 | 0.56 | 0.31 | 1.37 | -0.39 | 0.27 | r | 2000 Mar |
| 234.396 ............ | 53.538 | 17.15 | 1.45 | 0.012 | 1.01 | 0.010 | 0.01 | -1.89 | 0.07 | -1.75 | 0.46 | -1.64 | 0.17 | g |  |
| "..................... | " | 17.15 | 1.45 | 0.012 | 1.01 | 0.010 | 0.01 | -1.88 | 0.07 | -1.73 | 0.48 | -1.77 | 0.22 | g | 2000 Jan |
| . | " | 17.15 | 1.45 | 0.012 | 1.01 | 0.010 | 0.01 | -2.03 | 0.26 | -2.01 | 1.71 | -1.48 | 0.25 | r | 1999 May |
| 234.772 ............ | 53.952 | 18.73 | 1.17 | 0.018 | 0.82 | 0.014 | 0.00 | -0.90 | 1.72 | 0.25 | 5.01 | 0.09 | 0.53 | r | 2000 Mar |
| 237.117 ............ | 58.439 | 18.23 | 1.15 | 0.011 | 0.67 | 0.009 | 0.02 | -1.86 | 0.35 | -0.77 | 2.97 | -0.73 | 0.37 | S | 2000 Mar |
| 237.553 ........... | 41.717 | 17.55 | 1.35 | 0.052 | 0.99 | 0.040 | 0.05 | -1.41 | 0.32 | 0.74 | 0.35 | 1.37 | 0.13 | d | 2000 Jan |
| 237.637 ............ | 41.552 | 16.91 | 1.31 | 0.018 | 1.09 | 0.012 | -0.07 | -1.40 | 0.24 | -0.13 | 0.21 | 0.17 | 0.08 | s | 1999 May |
| 238.011 ............ | 35.428 | 16.63 | 1.28 | 0.052 | 1.03 | 0.051 | -0.01 | -1.38 | 0.13 | 0.37 | 0.44 | 0.52 | 0.10 | d | 2000 Jan |
| 243.202 ............ | 43.448 | 19.63 | 1.26 | 0.016 | 0.71 | 0.013 | 0.02 | -2.65 | 0.05 | -5.46 | 1.24 | -1.84 | 0.33 | g | 2001 Feb |
| 245.400 ............ | 63.057 | 19.72 | 1.17 | 0.026 | 0.79 | 0.022 | 0.04 | -1.51 | 0.07 | -2.45 | 1.30 | -1.79 | 0.41 | g | 2001 Feb |
| 245.536 ............ | 63.221 | 18.43 | 1.19 | 0.023 | 0.92 | 0.022 | 0.02 | -1.50 | 0.60 | -0.31 | 0.91 | -1.58 | 0.45 | s | 2000 Jan |
| 245.667 ............ | 63.208 | 19.27 | 1.51 | 0.025 | 1.09 | 0.021 | 0.00 | -1.13 | 1.16 | -0.55 | 1.30 | 0.70 | 0.28 | d | 2000 Jan |
| 257.693 ............ | 40.527 | 16.56 | 1.14 | 0.019 | 0.68 | 0.014 | 0.10 | -1.02 | 0.17 | 0.13 | 0.31 | -0.34 | 0.18 | s | 1999 May |
| 257.806 ............ | 40.420 | 18.69 | 1.53 | 0.016 | 1.03 | 0.016 | 0.09 | -2.00 | 17.88 | 0.84 | 1.91 | 0.74 | 0.28 | d | 2000 Jan |
| 263.954 ............ | 33.046 | 16.82 | 1.18 | 0.028 | 0.83 | 0.018 | -0.01 | -1.18 | 0.53 | -0.03 | 0.52 | -0.20 | 0.19 | S | 2000 May |
| 264.138 ............ | 42.307 | 16.74 | 1.15 | 0.019 | 0.93 | 0.007 | -0.05 | -1.01 | 0.36 | 1.02 | 0.57 | 0.73 | 0.28 | S | 1999 May |
| 268.718 ............ | 57.616 | 18.37 | 1.17 | 0.016 | 0.80 | 0.013 | 0.01 | -0.94 | 0.29 | -0.61 | 0.60 | -0.88 | 0.14 | g | 2000 Jan |
| 268.922 ............ | 58.157 | 18.91 | 1.20 | 0.010 | 0.66 | 0.010 | -0.01 | -1.75 | 0.29 | -0.76 | 1.76 | -1.09 | 0.21 | r | 2000 Jan |
| 271.998 ............ | 69.265 | 18.25 | 1.48 | 0.012 | 1.40 | 0.010 | -0.03 | -1.24 | 0.41 | -0.80 | 0.63 | -0.63 | 0.12 | g | 1999 May |
| 272.015 ............ | 69.457 | 17.63 | 1.38 | 0.009 | 1.01 | 0.008 | -0.09 | -2.80 | 0.05 | -0.85 | 0.06 | 0.12 | 0.02 | s | 1999 May |
| 278.771 ............ | 46.875 | 17.88 | 1.20 | 0.006 | 0.86 | 0.006 | 0.04 | -1.38 | 0.40 | -0.79 | 0.69 | -1.37 | 0.12 | g | 2000 May |
| 278.782 ............ | 46.819 | 17.09 | 1.25 | 0.007 | 0.96 | 0.007 | 0.03 | -1.17 | 0.09 | -0.93 | 0.24 | -1.14 | 0.05 | g | 2000 Jan |
| 279.076 ............ | 47.225 | 19.61 | 1.19 | 0.018 | 0.76 | 0.022 | 0.03 | -1.44 | 0.05 | -0.66 | 0.19 | -0.81 | 0.12 | s | 2001 Feb |
| 279.925 ............ | 36.066 | 18.93 | 1.12 | 0.013 | 0.73 | 0.011 | 0.04 | -1.64 | 0.05 | -2.44 | 0.97 | -2.23 | 0.33 | g | 2001 Feb |
| 280.395 ............ | 59.320 | 18.26 | 1.17 | 0.015 | 0.68 | 0.011 | 0.03 | -1.27 | 0.07 | -0.61 | 0.18 | -0.63 | 0.13 | r | 2001 Feb |
| 280.685 ............ | 59.934 | 17.84 | 1.15 | 0.011 | 0.76 | 0.013 | 0.03 | -0.86 | 0.10 | -0.80 | 0.24 | -1.63 | 0.30 | g | 2001 Feb |
| 282.327 ............ | 41.070 | 19.13 | 1.22 | 0.009 | 0.87 | 0.009 | -0.01 | -1.71 | 1.22 | -0.23 | 0.73 | -0.89 | 0.08 | S | 2000 May |

TABLE 6－Continued

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counts analytically and then use Monte Carlo simulations to calculate the error on their ratio (the line index) and to propagate through to the resultant metallicity error.

We derive pixel-by-pixel estimates of the measurement errors of the spectrum using IRAF's estimates of $\sigma$ for each extracted pixel, provided by the APSUM task. ${ }^{3}$ Analytic errors are calculated for the numerator and denominator of each spectral index, and then a Monte Carlo simulation is used to calculate the error on the line index. These errors are given in Mateo et al. (2003). We use the semianalytic error estimates to run 1000 Monte Carlo simulations to calculate the effect on the derived metallicity of changing the line index by an amount drawn from a Gaussian distribution with mean zero and $\sigma$ equal to the index error estimate. The standard deviation of the metallicity values derived from these simulations is given as the (random) error on the metallicity from each index in Table 6.

We have checked this error formalism by applying it to the error-degraded spectra of M3 Cud 250 described above and found that the resultant metallicity and quoted error were consistent with the known metallicity for this star and the deviation from its true metallicity. In addition, we have multiple observations of a small number of program stars on different runs and are able to compare directly the difference in derived metallicity and the derived errors. These also give results that are consistent with the errors.
${ }^{3}$ We take care to correctly propagate these errors when we combine different exposures, as IRAF's SCOMBINE and similar tasks do not.

## 8. DISTANCE MEASUREMENT

We calculate the distance to our giant stars by estimating their absolute magnitude, using the globular cluster $V-I$ giant branches of Da Costa \& Armandroff (1990). Our $M-T_{2}$ values transform accurately to $V-I$ (Morrison et al. 2000); we use the spectroscopic metallicity estimate and interpolate between cluster giant branches to obtain an estimate of the absolute magnitude $M_{V}$ at that $M-T_{2}$ color and metallicity.

We transform our dereddened Washington photometry to a $V$ magnitude using the relation

$$
V=T_{2}+0.8(M-T 2)
$$

(D. Geisler 2002, private communication). This equation was checked using the bright standards of Harris \& Canterna (1979), which have both $V$ and Washington magnitudes.

Distances are given in column (7) of Table 7. We calculate distance errors with a Monte Carlo calculation using the errors on metallicity and $M-T_{2}$. For the metallicity error, we add in quadrature the random error (col. [6] of Table 7) and 0.25 dex (a conservative estimate of the systematic calibration error). We find that the most significant contribution to the distance error is the metallicity error, as the positions of the globular cluster giant branches in the colormagnitude diagram are strongly dependent on the metallicity of the cluster. Distance errors for program stars are given in column (8) of Table 7.

TABLE 7
Metallicities and Distances for Spectroscopically Confirmed Giants

| (1) | $b$ <br> (2) | $[\mathrm{Fe} / \mathrm{H}]_{\text {phot }}$ <br> (3) | Error <br> (4) | $\begin{gathered} {[\mathrm{Fe} / \mathrm{H}]_{\text {spect }}} \\ (5) \end{gathered}$ | Error (6) | Distance (kpc) <br> (7) | Error (8) | Field (9) | Chip <br> (10) | X <br> (11) | $Y$ <br> (12) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 11.853 ........... | 51.950 | -0.88 | 0.09 | -1.06 | 0.27 | 21.71 | 1.97 | 10118bp517 | 2 | 772 | 1067 |
| 17.353 ........... | 46.505 | -1.71 | 0.09 | -1.21 | 0.26 | 16.03 | 1.45 | 10171bp467 | 1 | 1852 | 164 |
| 233.896 ......... | 32.321 | -1.70 | 0.06 | -1.05 | 0.28 | 18.67 | 0.77 | 12341 bp 321 | 1 | 661 | 1827 |
| 234.396 ......... | 53.538 | -2.84 | 0.16 | -1.89 | 0.26 | 36.91 | 4.97 | 12342bp539 | 4 | 879 | 1949 |
| 243.202 .......... | 43.448 | -3.03 | 0.19 | -2.65 | 0.25 | 75.20 | 4.24 | 12432bp438 | 4 | 241 | 2015 |
| 245.400 ......... | 63.057 | -1.55 | 0.19 | -1.51 | 0.26 | 54.56 | 7.07 | 12449bp632 | 3 | 340 | 267 |
| 268.718 ......... | 57.616 | -1.49 | 0.11 | -0.88 | 0.29 | 25.12 | 1.90 | 12690bp580 | 4 | 14 | 1710 |
| 271.998 ......... | 69.265 | -0.67 | 0.06 | -0.68 | 0.39 | 44.39 | 8.29 | 12724bp696 | 4 | 388 | 1658 |
| 278.771 ......... | 46.875 | -1.40 | 0.05 | -1.37 | 0.28 | 25.49 | 2.44 | 12790bp470 | 4 | 990 | 115 |
| 278.782 ......... | 46.819 | -1.26 | 0.06 | -1.15 | 0.25 | 19.41 | 1.79 | 12790bp470 | 4 | 869 | 579 |
| 279.925 ......... | 36.066 | -1.48 | 0.11 | -1.64 | 0.25 | 31.38 | 2.39 | 12797bp362 | 3 | 698 | 1068 |
| 280.685 ......... | 59.934 | -1.56 | 0.10 | -0.94 | 0.56 | 18.72 | 1.49 | 12808bp597 | 1 | 136 | 1661 |
| 289.842 ......... | 48.548 | -1.71 | 0.10 | -1.88 | 0.31 | 20.52 | 1.09 | 12900bp487 | 4 | 1359 | 785 |
| 304.491 ......... | 60.514 | -3.59 | 0.15 | -1.62 | 0.27 | 83.24 | 6.32 | $13051 \mathrm{bp6} 68$ | 4 | 137 | 2030 |
| 305.220 ......... | 61.239 | -1.84 | 0.08 | -1.82 | 0.36 | 24.39 | 3.33 | $13051 \mathrm{bp611}$ | 1 | 186 | 491 |
| 305.324 ......... | 60.577 | -1.76 | 0.10 | -1.32 | 0.31 | 16.55 | 1.91 | $13051 \mathrm{bp6} 68$ | 3 | 768 | 669 |
| 305.501 ......... | 60.647 | -1.01 | 0.08 | -0.99 | 0.39 | 34.17 | 5.67 | $13051 \mathrm{bp6} 68$ | 3 | 1478 | 1296 |
| 322.115 ......... | 39.907 | -1.36 | 0.09 | -1.28 | 0.28 | 11.65 | 1.12 | 13220bp398 | 1 | 118 | 679 |
| 329.487 ......... | -38.088 | -1.61 | 0.11 | -1.80 | 0.41 | 23.28 | 2.82 | 13291bm381 | 2 | 577 | 201 |
| 332.709 ......... | 46.838 | -1.11 | 0.06 | -1.18 | 0.33 | 21.02 | 1.58 | 13331 bp 468 | 4 | 146 | 69 |
| 333.498 ......... | 46.754 | -1.30 | 0.16 | -1.05 | 0.29 | 23.84 | 2.54 | 13331 bp 468 | 1 | 1702 | 615 |
| 338.849 ......... | 68.273 | -2.25 | 0.08 | -1.84 | 0.29 | 19.55 | 1.72 | 13396bp682 | 4 | 78 | 159 |
| 347.090 .......... | -49.452 | -1.65 | 0.08 | -1.28 | 0.45 | 18.51 | 1.43 | 13469bm493 | 1 | 271 | 1054 |
| 347.421 .......... | 53.306 | -1.53 | 0.12 | -1.30 | 0.32 | 15.22 | 1.83 | 13479bp533 | 4 | 603 | 823 |
| 347.683 ......... | 53.056 | -1.78 | 0.11 | -2.58 | 0.33 | 16.83 | 0.30 | 13479bp533 | 3 | 131 | 398 |
| 354.408 .......... | 66.307 | -0.80 | 0.07 | -0.57 | 0.39 | 13.01 | 1.18 | 13549bp662 | 4 | 766 | 234 |
| 355.889 .......... | 51.099 | -1.37 | 0.22 | -1.20 | 0.31 | 74.36 | 9.75 | 13564bp511 | 4 | 1099 | 1762 |
| 355.986 ......... | 51.162 | -1.54 | 0.09 | -1.26 | 0.27 | 16.84 | 1.55 | 13564bp511 | 4 | 1083 | 1015 |
| 356.151 ......... | 50.952 | -0.94 | 0.11 | -1.41 | 0.25 | 46.70 | 4.86 | 13564bp511 | 3 | 127 | 398 |
| 356.702 ......... | 51.228 | -1.61 | 0.10 | $--1.24$ | 0.63 | 39.20 | 6.78 | 13564bp511 | 1 | 498 | 1304 |

## 9. METALLICITY AND LUMINOSITY ESTIMATES OF HALO GIANT CANDIDATES

Figures 16 through 18 give examples of our spectroscopic luminosity classification technique. In all three figures the top panel shows the (pseudo-flux-calibrated) spectrum, while the other two panels are similar to Figure 9, but also show the program star's metallicity from each index. Figure 16 shows an example of a metal-poor halo giant, whose $[\mathrm{Fe} / \mathrm{H}]$ estimates from $\mathrm{Ca}_{\text {II }} \mathrm{K}$, Ca I $\lambda 4227$, and Mg are very close. Figure 17 shows a strong-lined dwarf star (both Ca I $\lambda 4227$ and MgH are very prominent), while Figure 18 is an example of a subdwarf whose $[\mathrm{Fe} / \mathrm{H}]$ from Ca I is almost a dex higher than the $[\mathrm{Fe} / \mathrm{H}]$ from $K^{\prime}$.
Table 6 summarizes the observations from spectroscopic runs described in § 2. The index values are given in Mateo et al. (2003); we give the photometric data for the star (also available via ADS). We add the observing run when the spectrum was obtained, the values of $[\mathrm{Fe} / \mathrm{H}]$ with errors obtained from each of the three spectroscopic indices and the star's luminosity classification.
Table 7 summarizes the observational data for the giants. If the star was observed multiple times, the data have been averaged, weighting by the errors. We give the final $[\mathrm{Fe} / \mathrm{H}]$ estimate (obtained from the spectroscopic $K^{\prime}$ and Mg indices as described in § 6), our distance measurement and its error.


Fig. 16.-Example of luminosity classification diagrams used at the telescope. Top panel shows the spectrum after the "pseudo-flux calibration." The middle and bottom panels are the same as Fig. 9 but also have the program star index values (large filled circle) and their errors plotted. This star $(1278.782 \mathrm{~b}+46.819)$ is a metal-poor giant whose metallicity measures from all three indices are very similar.


Fig. 17.-Example of luminosity classification, as in Fig. 16. Here (star $1237.553 \mathrm{~b}+41.717$ ) we see a strong-lined dwarf star. The MgH and Ca I features are very strong, and it can be seen in the middle and bottom panels that the metallicity estimate from both $\mathrm{Ca}_{\mathrm{I}}$ and MgH is much higher than the estimate from Ca II K.

Figure 19 shows the distribution in the Galaxy's $X-Z$ plane of our 30 spectroscopically confirmed giants. For comparison, we have also plotted all the halo objects from the compilation of Beers et al. (1995) and the location of the SDSS streams (Ivezić et al. 2000; Yanny et al. 2000) of BHB and RR Lyrae stars. It can be seen that our pencil-beam survey is already probing more of the outer halo than any previous study. Also, while we will need to carefully model our selection effects before we can be sure, there is no clear sign of the "edge" to the halo proposed by Ivezić et al. (2000); this may have been an artifact of the presence of the wellpopulated Sgr streams in the SDSS commissioning data.
An independent check of our metallicity and distance estimates is provided by star $1243.202 \mathrm{~b}+43.448$, which, at a distance of $74 \pm 4 \mathrm{kpc}$ and with a velocity of $240 \pm 54 \mathrm{~km}$ $\mathrm{s}^{-1}$ (Mateo 2003), is a likely member of the Sextans dwarf spheroidal galaxy. It lies within its tidal radius $\left(160^{\prime} \pm 50^{\prime}\right.$, Mateo 1998). The distance and heliocentric velocity of Sextans are 86 kpc and $227 \mathrm{~km} \mathrm{~s}^{-1}$ (Mateo 98), both within our quoted errors on these quantities.

## 10. COMPARISON OF SPECTROSCOPIC AND PHOTOMETRIC METALLICITIES

We now have two almost independent measures of $[\mathrm{Fe} / \mathrm{H}]$, photometric and spectroscopic. (The $M-T_{2}$ color contributes to both, but not strongly to the spectroscopic value.) It is illuminating to compare them. First we consider


Fig. 18.-Example of luminosity classification, as in Fig. 16. This star $(1263.954 \mathrm{~b}+33.046)$ is a subdwarf whose Ca I and $\mathrm{Mg} b / \mathrm{H}$ features are not as strong as in Fig. 17, but still give a significantly higher metallicity than Ca II K.


Fig. 19.-Location of our spectroscopically confirmed giants (stars) in the $X$ - $Z$ plane. Also shown (open circles) are the known halo objects from the compilation of Beers \& Sommer-Larsen (1995) and the SDSS stream discovered by Ivezić et al. (2000) and Yanny et al. (2000).


Fig. 20.-Comparison of [Fe/H] values used by Geisler et al. (1991) in his abundance calibration of the Washington system and updated values from the literature in 2001. Open circles are field giants, closed circles, globular cluster giants. The solid line shows exact equality between the two measures, while the dotted line shows the relation $[\mathrm{Fe} / \mathrm{H}]_{2001}=$ $[\mathrm{Fe} / \mathrm{H}]_{\text {Geisler }}$.
possible differences in derived $[\mathrm{Fe} / \mathrm{H}]$ due to different calibrations. When the Geisler, Claria, \& Minniti (1991) metal abundance calibration of the Washington system was published, the improved high-dispersion globular cluster abundance scale to which we have tied this work was not available. We made a check of both field stars and globulars used in the Geisler et al. (1991) calibration, to see whether published values have changed in the ensuing 10 years. Figure 20 shows that while the zero point of the field stars has not moved, the new globular cluster scale is approximately 0.2 dex more metal-rich on average than the cluster scale used by Geisler in 1991. Thus, we expect such a difference when comparing our photometric and spectroscopic metallicity measurements.

Figure 21 shows the comparison of photometric and spectroscopic metallicities for the 30 giants of Table 7 whose spectroscopic metallicity error is less than 0.5 dex. Where photometric and spectroscopic metallicities disagree by more than the errors, the spectrum was also visually compared with the spectra of standard stars. In only one case (a star with spectroscopic metallicity of -2.6 and photometric metallicity of -1.8 ) did we decide that the derived spectroscopic metallicity was likely to be incorrect; in all other cases the visual check of the spectroscopic metallicities confirmed their accuracy.
The two stars whose spectroscopic and photometric metallicities are most discrepant are both quite red for metal-poor stars $\left[\left(M-T_{2}\right)_{0}=1.36\right.$ and $1.45,[\mathrm{Fe} / \mathrm{H}]_{\text {phot }}=-3.6$ and -2.8 , respectively]. Because such stars are intrinsically rare and no globular clusters are known with $[\mathrm{Fe} / \mathrm{H}]<-2.5$, there are only three stars in the Geisler et al. (1991) calibration with $[\mathrm{Fe} / \mathrm{H}]$ (from updated measurements) less than -2.5 and $\left(M-T_{2}\right)_{0}$ greater than 1.2 , and no stars with $\left(M-T_{2}\right)_{0}$ greater than 1.35 . This, plus the fact that the


Fig. 21.-Comparison of photometric and spectroscopic $[\mathrm{Fe} / \mathrm{H}]$ values for our confirmed giants. Closed circles are stars with $\left(M-T_{2}\right)_{0}$ less than 1.29 ; open circles are redder stars where the Washington abundance calibration is less secure at the metal-poor end. The solid line shows the expected mean relation due to the revision of the globular cluster abundance scale, since our spectroscopic abundances are based on the new scale and the Washington calibration is based on the old scale.

Washington abundance calibration loses sensitivity for metal-poor stars at the red end, as can be seen by the convergence of the isoabundance lines, suggests that Washington abundances for such red, metal-poor stars should be viewed with caution. We have plotted such stars with open symbols in Figure 21.

For the remainder of the sample agreement between photometric and spectroscopic metallicities is reasonably good, giving a post facto check on the accuracy of our photometry, as well as the accuracy of our spectroscopic metallicities. As our sample of giants grows (and our cali-
brated photometry comes from more than one run, allowing direct checks of the accuracy of the photometry), we will revisit this issue.

## 11. SUMMARY

We have shown that, with spectra of sufficiently high $\mathrm{S} / \mathrm{N}$, it is possible to distinguish distant halo giants from foreground dwarfs of the disk, thick disk, and (most importantly) the halo. We use the Ca ir K line, the Са І $\lambda 4227$ line and the $\mathrm{Mg} b / \mathrm{MgH}$ feature near 5170 A to measure both metallicity and luminosity for our giant candidates. We calibrate the metallicity sensitivity of these three features using globular cluster giants and then use observations of field stars to derive an estimate of the accuracy of our calibration for well-exposed spectra. In the regions where each index has the most sensitivity this calibration error is $0.20-0.25$ dex. We then derive an estimate of the random error of each estimate for our program star spectra, where photon statistics are an important source of error. In general, we find that, for $\mathrm{S} / \mathrm{N}$ of $\sim 15$ pixel $^{-1}$, random errors of order 0.2 dex in metallicity are achieved.
Luminosity measurement, very important for these faint G and K stars, is done by comparison of the strength of the luminosity-dependent Ca I $\lambda 4227$ and $\mathrm{Mg} b / \mathrm{MgH}$ features with the strength of the Ca II K line, which has little luminosity sensitivity. Our error analysis allows us to determine the required $\mathrm{S} / \mathrm{N}$ for reliable discrimination at the telescope, thus making our observations of these faint stars as efficient as possible.
We present data for our first sample of halo giants, whose distances range from 15 to 83 kpc . This represents a significant increase in sampling of the Galaxy's outer halo.

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[^1]:    ${ }^{\text {a }}$ Chromospherically active star. This makes the $K^{\prime}$ index unusable because of emission in the core of the K line.
    ${ }^{\mathrm{b}} \mathrm{G} 251-53$ is a common proper-motion pair of $\mathrm{BD}+80245$, which has unusually low $\alpha$-element abundances, $[\alpha / \mathrm{Fe}]=-0.3$ (Carney et al. 1997), compared with the majority of halo stars, which have $[\alpha / \mathrm{Fe}] \simeq+0.4$.
    ${ }^{\text {c }}$ HD 134440 has low $\alpha$-element abundances, $[\mathrm{Ca} / \mathrm{Fe}]=0.22,[\mathrm{Mg} / \mathrm{Fe}]=-0.11$, $\operatorname{King} 1997$.
    ${ }^{\mathrm{d}} E(B-V)$ estimated using Schlegel et al. 1998 reddening, distance estimate, and reduction in line-of-sight reddening from Bond 1980. (1) Carbon et al. 1987; (2) Carney et al. 2001; (3) Alonso, Arribas, \& Martinez-Roger 1996; (4) Ryan 1992; (5) Schlegel et al. 1998; (6) Ivans et al. 2000; (7) Eggen 1998; (8) Geisler 1984; (9) Beveridge \& Sneden 1994; (10) Carney \& Aaronson 1979; (11) Tomkin and Lambert 1999; (12) Gratton et al. 1997; (13) Clementini et al. 1999; (14) King 1997; (15) Bessell 1990; (16) Cayrel de Strobel et al. 1997; (17) Twarog and AnthonyTwarog 1995; (18) this work.

[^2]:    ${ }^{2}$ It is perhaps worth noting that Mg is found to be depleted in some globular cluster giants (accompanied by oxygen and Al enhancements), resulting perhaps from deep mixing to the surface of material that has undergone ( $p$, gamma) reactions deep within the star after it has left the main sequence. We refer the reader to Da Costa (1997) for further discussion of this interesting topic. To our knowledge the effect has not been reported previously for dwarfs. Inspection of the catalog of abundances reported by Norris et al. (2001) finds three of the giants in our Table 2, all of which have $[\mathrm{Mg} / \mathrm{Ca}] \sim 0.0$.

