Clues to the Metallicity Distribution in the Galactic Bulge: Abundances in MOA–2008–BLG–310S and MOA–2008–BLG–311S

Judith G. Cohen², Ian B. Thompson³, Takahiro Sumi⁴, Ian Bond⁵, Andrew Gould⁶, Jennifer A. Johnson⁷, Wenjin Huang⁸ & Greg Burley³

ABSTRACT

We present abundance analyses based on high dispersion and high signal-to-noise ratio Magellan spectra of two highly microlensed Galactic bulge stars in the region of the main sequence turnoff with $T_{\text{eff}} \sim 5650$ K. We find that MOA–2008–BLG–310S has $[\text{Fe/H}] = +0.41 \pm 0.09$ dex and MOA–2008–BLG–311S has $+0.26 \pm 0.09$ dex. The abundance ratios for the $\sim$20 elements for which features could be detected in the spectra of each of the two stars follow the trends with $[\text{Fe/H}]$ found among samples of bulge giants. Combining these two bulge dwarfs with the results from previous abundance analysis of four other Galactic bulge turnoff region stars, all highly magnified by microlensing, gives a mean $[\text{Fe/H}]$ of $+0.29$ dex. This implies that there is an inconsistency between the Fe-metallicity distribution of the microlensed bulge dwarfs and that derived by the many previous estimates based on surveys of cool, luminous bulge giants, which have mean $[\text{Fe/H}] \sim -0.1$ dex. A number of possible mechanisms for producing this difference are discussed. If one ascribes this inconsistency to systematic

¹This paper includes data gathered with the 6.5 meter Magellan Telescopes located at Las Campanas Observatory, Chile.

²Palomar Observatory, Mail Stop 105-24, California Institute of Technology, Pasadena, Ca., 91125, jlc@astro.caltech.edu

³Carnegie Observatories of Washington, 813 Santa Barbara Street, Pasadena, Ca. 91101, ian.burley@ociw.edu

⁴Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, Japan; sumi@stelab.nagoya-u.ac.jp

⁵Institute for Information and Mathematical Sciences, Massey University, Auckland, New Zealand; I.A.Bond@massey.ac.nz

⁶Department of Astronomy, Ohio State University, 140 W. 18th Ave., Columbus, OH 43210; gould@astronomy.ohio-state.edu and Institute d’Astrophysique de Paris, 98bis Blvd Arago, Paris, 75014, gould@astronomy.ohio-state.edu

⁷Department of Astronomy, Ohio State University, 140 W. 18th Ave., Columbus, OH 43210; jaj@astronomy.ohio-state.edu

⁸Palomar Observatory, Mail Stop 105-24, California Institute of Technology, Pasadena, Ca., 91125, current address: University of Washington, Department of Astronomy, Box 351580, Seattle, Washington, 98195-1580, hwenjin@astro.washington.edu

¹We adopt the usual spectroscopic notations that $[A/B] \equiv \log_{10}(N_A/N_B)_\odot - \log_{10}(N_A/N_B)_\odot$, and that $\log[e(A)] \equiv \log_{10}(N_A/N_H) + 12.00$, for elements $A$ and $B$. 
errors in the abundance analyses, we provide statistical arguments suggesting that a substantial systematic error in the Fe-metallicity for one or both of the two cases, bulge dwarfs vs bulge giants, is required which is probably larger than can realistically be accommodated.

Subject headings: gravitational lensing – stars: abundances – Galaxy: bulge

1. Introduction

High-magnification microlensing events present a rare opportunity to obtain high resolution spectra of otherwise extremely faint dwarfs in the Galactic bulge, which would require of order 100 hours of observations on 8m class telescopes under ordinary circumstances. Microlensing is itself very rare, with only a fraction \( \tau \sim 10^{-6} \) of stars being microlensed at any given time, even toward the Galactic bulge where the density of lenses is exceptionally high. Events that are magnified by a factor \( A \) are rarer still by a factor \( A^{-1} \). And finally, the high-magnification lasts only \( A^{-1} t_E \), where \( t_E \sim 30 \) days is the Einstein timescale of the event. So there are formidable problems predicting high-magnification episodes sufficiently far in advance to arrange spectroscopic observations from 8m class telescopes.

Nevertheless, two groups, Microlensing Observations in Astrophysics (MOA) and the Optical Gravitational Lens Experiment (OGLE) find a total of about 800 microlensing events per year, of which the Microlensing Follow Up Network (\( \mu \)FUN) is able to identify about 10 as high-magnification events. During the 2008 season, the additional challenges posed by getting spectra on short notice were overcome for three of these events, bringing the total number of bulge dwarfs with high-magnification spectra to seven. There are four published analyses: OGLE–2006–BLG–265S (Johnson et al. 2007), OGLE–2007–BLG–349S (Cohen et al. 2008), MOA–2006–BLG–099S (Johnson et al. 2008), and OGLE–2008–BLG–209S (Bensby et al. 2009). In addition, there is a spectrum of OGLE-2007-BLG-514S taken by M. Rauch and G. Becker with an as yet unpublished analysis by C. Epstein et al..

Here we analyze the two remaining high-mag bulge-dwarf spectra from the 2008 season, MOA–2008–BLG–310S and MOA–2008–BLG–311S, which, remarkably, peaked on successive nights over Africa and were both observed as they were falling from their peak at the beginning of the Chilean night using the Magellan Clay telescope. With the addition of these two stars, the sample microlensed bulge main sequence turnoff region stars with high resolution, high quality spectra and published detailed abundance analysis becomes six stars; we refer to them collectively as the six microlensed dwarfs.

The ability to obtain high resolution, high quality spectra of Galactic bulge stars and to carry

\[\text{http://www.astronomy.ohio-state.edu/~microfun/}\]
out a detailed abundance analysis offers an unbiased way to determine the metallicity distribution of stars in the Galactic bulge, as well as their detailed chemical inventory. The goal of the present paper is to carry out detailed abundance analyses for the two additional microlensed bulge dwarfs. Then in we use the six microlensed dwarf sample to study the bulge metallicity distribution function as well as their abundance ratios, and to compare them to the results obtained by a number of surveys of giants in the Galactic bulge.

2. Observations

MOA–2008–BLG–310S and MOA–2008–BLG–311S were observed on two consecutive nights in July 2008 using the MIKE spectrograph on the 6.5 m Magellan Clay Telescope at the Las Campanas Observatory by I. Thompson and G. Burley. Details of the exposures are given in Table 1. Spectroscopic exposures for MOA–2008–BLG–311S began at UT 22:58 just after sunset at airmass 1.93 (4.1 hours east of the meridian, so the initially large airmass decreased quickly) when it was magnified by a factor of 190; the star was just past its maximum brightness of $I \sim 13.5$ mag and fading at that time. The photometry of this microlensing event is consistent with a point source being magnified by a perfect point lens.

Spectroscopic exposures of MOA–2008–BLG–310S began with MIKE the following night at UT 22:51 at airmass 1.87 at the same hour angle as for MOA–2008–BLG–311S. MOA–2008–BLG–310S was brighter than MOA–2008–BLG–311S at the time of observation by $\sim 0.8$ mag. A narrower slit 0.5 arcsec wide was used to isolate MOA–2008–BLG–310S from a close companion roughly 2 mag fainter. Fortunately the seeing that night was very good (0.6 arcsec) after the first half hour (i.e. once the airmass became reasonable), and the companion rotated further away from the slit with time. Thus, even with the narrower slit and consequently higher spectral resolution, a high signal-to-noise ratio per spectral resolution element was achieved for the spectrum of this star.

The light curve of MOA–2008–BLG–310S shows pronounced finite-source effects, with the lens exiting the limb of the source about 20 minutes before the start of spectroscopic observations. In addition, the light curve shows much smaller deviations from standard point-lens microlensing due to a companion to the lens (J. Janczak et al. 2009, in prep). Johnson et al. (2009, in preparation) has explored the impact of differential amplification across the surface of a dwarf near the main sequence turnoff as it affects an abundance analysis; she finds it to be negligible compared to the uncertainties in the abundances.

3. Stellar Parameters

The microlensed bulge dwarfs suffer from substantial reddening whose exact value is unknown. We therefore rely purely on their spectra to determine their stellar parameters. The classical technique of excitation equilibrium for the set of the many Fe I lines measured is used to find $T_{\text{eff}}$. 

Then the microturbulent velocity $v_t$ is set by requiring the deduced Fe abundance to be independent of the equivalent width $W_\lambda$ for the same set of lines. The surface gravity is set by requiring ionization equilibrium between neutral and singly ionized Fe; the ionization equilibrium for Ti in both of the stars is then extremely good. If the deduced [Fe/H] is substantially different from that assumed to construct the model atmosphere, the process is repeated with the [Fe/H] determined from the initial pass used for the model atmospheres. Throughout this process, we choose to ignore lines with $W_\lambda$ exceeding 130 mÅ due to the difficulty of properly including their damping wings in the $W_\lambda$ measurements. Features bluer than 5200 Å were ignored unless the species had very few other detected lines as the signal-to-noise ratio decreases rapidly at bluer wavelengths due to the high reddening along the line of sight to the Galactic bulge.

Because the spectra are not perfect, and being concerned about the convergence of this scheme onto the correct set of stellar parameters, we decided to develop a technique for determining [Fe/H], at least approximately, that might bypass some of these issues and indicate the magnitude of some of the uncertainties in a more direct fashion. Following in the spirit of the line ratio method developed by Gray & Johanson (1991) and used by Biacco, Frasca, Catalano & Marilli (2007), we looked for something easy to measure based purely on aspects of the spectrum that have a strong dependence on metallicity, but little dependence on any other stellar parameter. As a guide we constructed plots based on detailed abundance analyses of the behavior of weak lines of species with many detected absorption lines as a function of the set of adopted stellar parameters $T_{\text{eff}}$, $\log(g)$, [Fe/H] of the model atmosphere, and $v_t$ that would enable us to isolate metallicity from them. Figure 2 illustrates the best case we found for stars in the region of the main sequence turnoff, namely [Fe/H] derived from Fe I absorption lines with high excitation ($\chi > 4$ eV), which show low sensitivity to changes in $T_{\text{eff}}$ of $\pm250$ K or of $\log(g)$ of $\pm0.5$ dex within the regime of interest. Although not shown on the figure, we note that increasing [Fe/H] of the model atmosphere by 0.5 dex increases the deduced [Fe/H] by only 0.05 dex. Using high excitation Fe I lines, the final derived [Fe/H] from a detailed abundance analysis is bound to be close to the true value even if the adopted stellar parameters are slightly off. The weak dependence of the behavior of such lines on $T_{\text{eff}}$ is a result of the competition between ionizing Fe I when $T_{\text{eff}}$ is increased versus increasing the population in the high excitation state from which the absorption features arise. Fe II lines with $\chi \sim 0$ eV show a similar behavior with $T_{\text{eff}}$, but have much more sensitivity to changes in $\log(g)$ than do Fe I lines.

The resulting stellar parameters for MOA–2008–BLG–310S and MOA–2008–BLG–311S are listed in Table 2, which also gives the slopes between deduced [Fe/H] abundances and the excitation potential, $W_\lambda$, and $\lambda$ of the set of Fe I lines with $W_\lambda < 130$ mÅ. We see that extremely good results (i.e. almost flat relations with slopes very close to 0) were obtained for the first two (primarily sensitive to $T_{\text{eff}}$ and to $v_t$ respectively). The slope with wavelength for MOA–2008–BLG–310S is somewhat larger than ideal but the correlation coefficient is low ($< 0.15$), and the total change over the span of 2600 Å covered is only 0.07 dex. The uncertainty in $T_{\text{eff}}$ is related to the first slope, which decreases by $\sim0.05$ dev/eV when $T_{\text{eff}}$ is increased by 250 K in this regime. Assuming a
reasonable sample of low excitation Fe I lines, so that the range of the measured lines covers $\sim 4$ eV, we set the uncertainty in $T_{\text{eff}}$ to 100 K. The uncertainty in log($g$) then follows by considering the error resulting in ionization equilibrium of Fe I should $T_{\text{eff}}$ be off by 100 K, which has to be compensated for by changing log($g$). There is an additional smaller uncertainty in log($g$) arising from the uncertainty in the value of [Fe/H](Fe I) – [Fe/H](Fe II) itself. We find an uncertainty in log($g$) of 0.2 dex in log($g$) is appropriate.

We note that a fit to the H$\alpha$ profile in MOA–2008–BLG–310S, the star with the higher SNR spectrum, indicates $T_{\text{eff}} \sim 5500$ K, 120 K less than that derived from the Fe I line analysis. We also compare our derived values of $T_{\text{eff}}$ with those that would be inferred from the photometry of the two microlensed bulge dwarfs. Light curves were obtained in two colors, $V$ and $I$, by the $\mu$FUN collaboration for MOA–2008–BLG–310S and for MOA–2008–BLG–311S during the microlensing event as part of an effort to detect planets. The color of red clump stars in the field around each of the microlensed stars is easily determined. The comparison of instrumental ($V - I$) and $I$ of the red clump and the microlensed star then yield ($V - I$)$_0$ and $I_0$ of the star, under the assumption that it suffers the same extinction as the clump. If the microlensed star is further assumed to lie at the same distance as the clump, then the star’s absolute magnitude $M_I$ can be calculated. This yields ($V - I$)$_0 = 0.70$ mag for MOA–2008–BLG–310S and ($V - I$)$_0 = 0.66$ mag for MOA–2008–BLG–311S, with $I_0 = 17.94$ mag for MOA–2008–BLG–310S and 18.37 mag for MOA–2008–BLG–311S; $I$ is in the Cousins system. The Sun has $V - I = 0.688 \pm 0.014$ mag [Holmberg, Flynn & Portinari 2006], which would suggest that $T_{\text{eff}}$ for these two microlensed stars is quite close to that of the Sun. Given the uncertainties in the photometry and the probability of small spatial variations in the reddening across the field, this is in good agreement with the $T_{\text{eff}}$ derived directly from the spectra of MOA–2008–BLG–310S and of MOA–2008–BLG–311S of Table 2. These independent determinations of $T_{\text{eff}}$, together with their uncertainties, are summarized in Table 3.

We consider whether the derived parameters are consistent with the star being in the Galactic bulge by comparing log($g$) derived from the spectra with that derived from the photometry. $I_0$ is converted into a total luminosity assuming a distance to the Galactic center of 8 kpc. Then using the derived $T_{\text{eff}}$, and assuming a mass of 1$M_\odot$, we predict log($g$)(phot). The agreement between log($g$)(phot) and log($g$)(spec) is reasonable, with differences of 0.1 dex MOA–2008–BLG–310S, and 0.3 dex for MOA–2008–BLG–311S.

The ages of the microlensed bulge dwarfs are determined by comparing $M_I$ as a function of $T_{\text{eff}}$ from the relevant [Fe/H] and [$\alpha$/Fe] isochrones of the grid of the Dartmouth Stellar Evolution Database [Dotter et al. 2008], as shown in Fig. 1. The results for MOA–2008–BLG–310S and MOA–2008–BLG–311S are given in the last column of Table 1; they are consistent to within the errors with that of the Galactic bulge population inferred from HST imaging, $\sim 10$ Gyr, by Feltzing & Gilmore (2000), see also Zoccali et al. (2003).

\footnote{The dereddened red clump in the Galactic bulge is assumed to have $I_0 = 14.32$ mag and ($V - I$)$_0 = 1.05$ mag.}
4. Abundance Analysis

Once the stellar parameters were determined, the abundance analysis was carried out in a manner identical to that for OGLE–2007–BLG–349S as described in Cohen et al. (2008); in particular it was a differential analysis with respect to the Sun. In preparing the line list only features redder than 5200 Å were used, unless there were none that red for a particular species, due to increased crowding toward the blue and to the high reddening. Lines with $W_\lambda > 130$ mÅ were rejected unless the species did not have at least a few suitably weak lines. The exceptions are the 5680 Å Na doublet and the K I resonance line at 7700 Å in both stars. Also one Mg I, one Si I line, and the only two Cu I lines detected in MOA–2008–BLG–310S, each of which had $W_\lambda < 140$ mÅ, were retained. The equivalent widths are given in Table 4; their major uncertainty results from the definition of the continuum level.

We used a current version of the LTE spectral synthesis program MOOG (Sneden 1973). We employ the grid of stellar atmospheres from Kurucz (1993) with [Fe/H] = 0.0 and +0.5 dex having solar abundance ratios without convective overshoot (Castelli & Kurucz 2003) and with the most recent opacity distribution functions. Non-LTE corrections were not included, as this is a differential analysis with respect to Sun, and the stellar parameters of both of these stars are fairly close to those of the Sun. Hyperfine structure corrections were used as appropriate; see Cohen et al. (2008) for details.

The deduced abundances for MOA–2008–BLG–310S and for MOA–2008–BLG–311S are given in Tables 5 and 6 respectively, with derived absolute abundances (second column), the abundances relative to the Sun (fifth column), and the abundance ratios [X/Fe] (seventh column). The abundance ratios use either Fe I or Fe II as the reference depending on the ionization state and mean excitation potential of the measured lines of species under consideration. The 1σ dispersion around the mean for each species is given as $\sigma_{obs}$. This is calculated from the set of differences between the deduced solar abundance for the species in question and that found for a microlensed bulge dwarf for each observed line of the species. Thus neither random nor systematic errors in the $gf$ values contribute to $\sigma_{obs}$.

While the absolute abundance for a given species listed in Tables 5 and 6 will be affected by any systematic error in the $gf$ values of the lines we use here, relative abundances [X/Fe] will not since we have carried out a differential analysis with respect to the Sun. An uncertainty for [X/Fe] for each species, $\sigma_{pred}$, is calculated summing five terms combined in quadrature representing a change in $T_{eff}$ of 100 K, the corresponding uncertainty in log($g$) of 0.2 dex, a change in $v_t$ of 0.2 km s$^{-1}$, and a potential 0.25 dex mismatch between [Fe/H] of OGLE–2007–BLG–349S versus the value +0.5 dex of the model atmospheres we are using. (Tables 3 and 4 of Cohen et al. 2008 give the values of these four individual terms for each species.) The fifth term, the contribution for errors

---

4The NaD lines are too corrupted by interstellar features along the line of sight through the disk to the bulge, and were ignored.
in $W_{\lambda}$, is set to 0.05 dex if only one or two lines were measured; for a larger number of detected lines we adopt $\sigma_{\text{obs}}/\sqrt{N(\text{lines})}$ for this term. This is added in quadrature to the other four terms to determine our final uncertainty estimate given in the final column of Table 5 and of Table 6. We note that the total uncertainty in [Fe/H] so derived is 0.09 dex when the large set of Fe I lines is used.

The key result of the abundance analysis is the high Fe-metallicity found for the two microlensed Galactic bulge stars in the region of the main sequence turnoff, $[\text{Fe/H}] = +0.41$ dex for MOA–2008–BLG–310S and $+0.26$ dex for MOA–2008–BLG–311S. The abundance ratios are also of great interest. Figures 3, 4, and 5 show selected abundance ratios as a function of $[\text{Fe/H}]$ for the six microlensed bulge dwarfs. These are compared with abundance ratios from surveys of Galactic bulge giants by Fulbright, McWilliam & Rich (2007), Rich & Origlia (2005), Lecureur et al. (2007), and Rich, Origlia & Valenti (2007). The figures demonstrate that to within the uncertainties microlensed bulge dwarfs have abundance ratios $[X/\text{Fe}]$ consistent with those of Galactic bulge giants at the same Fe-metallicities. Comparisons between bulge giants and thick and thin disk stars are given by Fulbright, McWilliam & Rich (2007) and Lecureur et al. (2007), while detailed studies separating thick and thin disk stars, as well as halo stars, via their abundance ratios and trends with $[\text{Fe/H}]$ include Reddy et al. (2003), Mashonkina et al. (2004), and Bensby et al. (2005).

5. The Metallicity Distribution of the Galactic Bulge

We have presented detailed abundance analyses for two additional microlensed bulge main sequence turnoff region stars, so there are now six that have been observed at high spectral resolution within the past three years and for which detailed abundance analyses have been completed; the references for the additional four are given in §1. Only one of the six falls below solar metallicity, at $[\text{Fe/H}] = -0.32$ dex; all the others are well above solar, with the mean of the six being $\langle [\text{Fe/H}] \rangle = +0.29$ dex.

The positions on the sky of the six microlensed bulge dwarfs are shown in Figure 6. (The magnitude of their radial velocities are also indicated on this figure.) The location of Baade’s Window is marked. This is the field closest to the center of the Milky Way with reddening low enough that its bulge giants can be studied in detail in the optical with the current generation of large telescopes, and has thus been the subject of many recent surveys at the VLT (see, e.g. Zoccali et al. 2008) and at Keck (Fulbright, McWilliam & Rich 2006, among others). The circle marks the region with projected Galactocentric distance equal to that of Baade’s Window. It is important to note that five of the six microlensed bulge dwarfs are slightly outside that circle; only one is slightly within it. This means that the population we are sampling via microlensing should be essentially identical to the population sampled by studies of the giants in Baade’s Window. Zoccali et al. (2008) detected a small radial gradient in the mean metallicity with Galactocentric distance of 0.6 dex/kpc (0.08 dex/deg on the sky at the distance of the Galactic center). The gradient was established between Baade’s Window and bulge fields with larger projected $R_{\text{GC}}$. 
This would suggest that the mean Fe-metallicity of the sample of microlensed bulge dwarfs should be ~0.05 dex lower than that of Baade’s Window.

Zoccali et al. (2008) recently redetermined the Fe-metallicity distribution function in Baade’s Window using a sample of 204 luminous K giants with $14.2 < I < 14.7$ mag spanning a wide range in $V-I$ color ($1.53 < (V-I) < 2.62$ mag) so as to cover the full metallicity range within the stellar population of the Galactic bulge. There is also a sample of ~200 red clump giants in the Baade’s Window discussed in Lecureur et al. (2007). Red clump stars are biased against low metallicities, where RR Lyrae and blue horizontal branch stars would be expected instead, but should not be biased at the [Fe/H] values relevant here, [Fe/H] > −1 dex. Zoccali et al. (2008) combine the two datasets for a total sample of ~400 giants in this field.

Figure 7 compares the Fe-metallicity distribution function recently determined by Zoccali et al. (2008) in Baade’s Window with that of the six microlensed bulge dwarfs. The distributions are clearly different. The microlensed bulge dwarfs reveal a significantly higher mean Fe-metallicity than do the giants studied by Zoccali et al. (2008), who find a mean [Fe/H] of −0.04 dex for the 204 K giants and +0.03 dex for the red clump stars from Lecureur et al. (2007). This is considerably lower than that of the six microlensed bulge dwarfs. Furthermore, K and M giants closer to the Galactic center than Baade’s Window at $(l, b) = (0^\circ, -1^\circ)$ have been probed through high resolution infrared spectroscopy by Rich, Origlia & Valentí (2007), who also find a low mean Fe-metallicity, −0.22 dex, and no sign of a radial gradient in metallicity for $R_{GC}$ inward from Baade’s Window (see also Cunha & Smith 2006).

To evaluate the statistical significance of this difference in Fe-metallicity, we drew six stars at random from the sample of Zoccali et al. (2008), eliminating stars in the globular cluster NGC 6822, which is in Baade’s Window, and also those with highly uncertain [Fe/H] as indicated by the quality codes in their table. We took the average [Fe/H], which we call the six star mean. Note that the microlensed bulge star with by far the lowest [Fe/H] is actually a subgiant; it is the only subgiant among the six and is quite discrepant in [Fe/H] from the other five microlensed bulge dwarfs. The results for 40,000 such trials are given in Table 7 as the percentage of trials where the mean [Fe/H] for six stars drawn from the bulge giant sample equaled or exceeded that of the set of six microlensed bulge dwarfs.

If the [Fe/H] values of the large sample of bulge giants from Zoccali et al. (2008) are correct, and those of the six microlensed dwarfs are correct as well, then the probability that the two metallicity distribution functions are identical is very small, $4 \times 10^{-3}$, ignoring any radial gradient, which would further reduce the tabulated probabilities for metallicity increasing as Galactocentric radius decreases. A K-S test also indicates a very low probability that the two metallicity distributions are the same, 1.9%. However, if there are systematic errors in the metallicity scale of either (or of both), and they act in the right direction, the probability of this happening by chance increases. Therefore Table 7 also contains the probability in the case of systematic offsets of the correct sign ranging from 0.05 to 0.20 dex in size. A systematic difference in Fe-metallicity scale between the
two samples of 0.20 dex such that either the bulge giant metallicities are underestimated or those of the microlensed dwarfs are overestimated is required before the probability reaches 20%.

Zoccali et al. (2008) quotes a “conservative” uncertainty in [Fe/H] of an individual giant as ±0.2 dex, including possible systematic errors. A substantial systematic error in [Fe/H] is required to produce consistency between the microlensed bulge stars and the K (and M) giant samples. If only $T_{\text{eff}}$ is changed and one looks at the Fe-metallicity derived from Fe I lines (which is only logical, since there are far fewer Fe II lines detectable), a 0.2 dex change corresponds to a 400 K systematic error for the microlensed stars near the main sequence turnoff, as was shown in Figure 2, and to at least a 500 K systematic error if the problem lies in the cool giants, as at such low temperatures, iron is almost entirely neutral.

This level of systematic error is larger than the uncertainty in the absolute Fe-metallicity of the microlensed dwarfs, as their spectra can be compared directly to the solar spectrum. Bensby et al. (2009) includes a comparison of [Fe/H] for the previously published four microlensed bulge dwarfs derived independently, with different codes, different grids of model atmospheres, and different schemes for determining the stellar parameters, by T. Bensby, J. Cohen, and J. A. Johnson; the agreement among the analyses by the three independent groups is quite good, ±0.06 dex. On the other hand, the analysis of the cool giants and the determination of their stellar parameters is much more difficult. However, the required error in $T_{\text{eff}}$ for the bulge giants is even larger, and seems very unlikely. Furthermore many independent groups have surveyed giants in the Galactic bulge, with similar results as to the mean Fe-metallicity, so there is no reason to assign the required systematic error to them.

There are a number of consistency checks that have been or could be carried out to test the validity of the absolute Fe abundances between the bulge giants and the microlensed dwarfs. The scale of the Fe transition probabilities is not relevant for the dwarfs, as a differential solar analysis was used. But it is for the giants; Fulbright, McWilliam & Rich (2006) used a differential analysis with respect to the well studied giant Arcturus, while Lecureur et al. (2007) use the spectrum of the metal-rich giant $\mu$ Leo to derive pseudo-$gf$ values appropriate for their method of measuring $W_{\lambda}$ and their grid of model atmospheres, while their absolute scale for [Fe/H] is set by taking [Fe/H] for this star as +0.30 dex. Checks of the determination of the continuum level in the giant spectra, where this is quite difficult, could be carried out with very high quality spectra of a few bulge giants. Differences between the model atmosphere grids are probably not the cause as several independent groups have participated both for the dwarfs and for the giants. However, systematic problems affecting all the chosen model atmosphere grids as $T_{\text{eff}}$ decreases such as overionization of Fe could be contributing. Arguments that studies of members of a single open or globular cluster at a wide range of luminosities show no such effect (see e.g. Santos et al 2009 vs. Boesgaard, Jensen & Deliyannis 2009) are often not relevant to the present case when examined in detail. For example, Pasquini et al. (2004) studied giants and dwarfs in the open cluster IC 1651 with [Fe/H] +0.10 dex. However, their coolest and most luminous giant is several hundred K hotter in $T_{\text{eff}}$ and 0.4 dex higher in log($g$) than the hottest and least luminous of the bulge giants in the sample of
Fulbright, McWilliam & Rich (2006). Stars near the RGB tip are very rare, and are unlikely to be found in any open cluster, while no globular cluster with [Fe/H] > +0.1 dex is known in the Galaxy. Furthermore the best abundances for the most metal-rich clusters come from dropping in luminosity to the RHB, where $T_{\text{eff}}$ is considerably higher, and avoiding the RGB tip giants completely (see, e.g., Cohen et al. 1999).

There is thus a clear discrepancy between the metallicity distribution function in the Galactic bulge as sampled by microlensed main sequence turnoff region stars and by luminous K and M giants. While still more microlensed dwarfs with detailed abundance analyses are highly desired to improve the statistics, we assume that this difference is real and is not the result of systematic errors producing suitable offsets in [Fe/H] derived from the abundance analyses.

In our earlier paper Cohen et al. (2008) we offered the suggestion that the highest metallicity giants have such high mass loss rates that they do not get to the RGB tip before losing their entire envelope. Possible evidence against this hypothesis is presented by Zoccali et al. (2008) on the basis of the luminosity function along the RGB; Clarkson et al. (2008) comment that the metallicity distribution of the bulge giants and of main sequence stars inferred from ACS/HST photometry are consistent with each other. An additional possibility is that we are sampling a “young” and metal-rich stellar population such as that found within the inner 40 pc, where rather surprisingly massive young clusters exist (Figer et al. 2002), presumably fed, at least in part, by mass loss from bulge giants. This runs into the problem that the corresponding high luminosity stars from such a population are not present in Baade’s Window, as reinforced by the very recent ACS/HST study of the Galactic bulge by Clarkson et al. (2008).

A similar argument applies for any proposed special component of the central region of our Galaxy such as an extension of the disk. Luck, Kovtyukh & Andrievsky (2006) determined the metallicity gradient for the Galactic disk from analysis of a large sample of Cepheid variables outside 4 kpc from the center to be $-0.06$ dex kpc$^{-1}$. It is interesting to note that their deduced [Fe/H] reached +0.3 dex at $R_{GC} = 4$ kpc, and if their linear fit is extrapolated inward, would reach +0.5 dex at $R_{GC} = 1$ kpc. A similarly metal-rich population of solar neighborhood disk stars whose highly eccentric orbits have pericentric distances as small as 3 kpc was identified by Grenon (1999) and Pompeia, Barbuy & Grenon (2002). These super metal-rich old dwarfs have [Fe/H] reaching up to +0.4 dex and mean distance from the Galactic plane of only 220 pc. But a rather puffed up disk would be required to contribute significantly at Baade’s Window, which is at $b \sim -4^\circ$ (560 pc). Certainly over a very large range in $R_{GC}$ the vertical scale height of the thin disk is smaller than that.

Another possibility is that the disk and/or halo contamination in the giant samples in Baade’s Window is larger than that calculated from Galactic models by Zoccali et al. (2008) and others. Little is known of the detailed structure of the disk and bulge in the region of the Galactic center. Although disk and halo contamination of the giant samples are believed to be small based on calculations using models of the stellar population of the Galaxy (see, e.g., Zoccali et al. 2008), the
uncertainty in such corrections might be large. The extensive proper motion studies in bulge fields
(see, e.g. Clarkson et al. 2008) give good determinations of the foreground disk contamination,
but cannot easily address the possible presence of the disk within the bulge itself provided it
makes a minor contribution to the total stellar population in the bulge. Disk contamination in the
microlensed sample, which is a sample of background sources, must be smaller than that of the in
situ giant samples, which probe the long line of sight to the center; the probability of microlensing
for a foreground disk star is much smaller than for a star in the bulge itself, hence very biased
strongly against disk stars.

6. Summary

We present detailed abundance analyses based on high dispersion and high signal-to-noise ratio
MIKE spectra taken with the 6.5 m Magellan Clay Telescope of two highly microlensed Galactic
bulge stars in the region of the main sequence turnoff. Our stellar parameters were derived ignoring
the available photometry out of concern for the high and uncertain reddening toward the bulge,
and rely only on the spectra themselves. They are based on the classical criteria of Fe excitation
equilibrium, and the ionization equilibrium of Fe and of Ti, and are consistent to within the adopted
errors with that inferred from the Hα profile for the star with the higher quality spectrum, MOA–
2008–BLG–310S. We deduce \( T_{\text{eff}} \) near 5650 K for both of these stars. MOA–2008–BLG–310S and
MOA–2008–BLG–311S appear to be at the distance of the bulge with age \( \sim 9 \) Gyr.

We suggest that the use of high excitation (\( \chi > 4 \text{ eV} \)) Fe I lines is the measure of metallicity
most independent of the exact choice of values for stellar parameters for such stars among the
various possibilities we explored. We note that the available \( V, I \) photometry for the two stars
supports our choice of \( T_{\text{eff}} \) for each to within the photometric errors and the uncertainty of the
reddening determination, which is based on red clump stars in the bulge in the field around each
of the microlensed dwarfs.

We carry out a detailed classical abundance analysis using 1D stellar model atmospheres and
ignoring non-LTE. Since this is done differentially to the Sun and the two stars both have \( T_{\text{eff}} \) within
160 K of that of the Sun and \( \log(g) \) within 0.3 dex of the Sun, these choices seem appropriate.
We find that MOA–2008–BLG–310S has \([\text{Fe/H}] = +0.41 \pm 0.09\) dex and MOA–2008–BLG–311S has
+0.26\pm0.09\) dex. The abundance ratios for the \( \sim 20 \) elements for which features could be detected in
the spectra of each of the two stars follow the trends with \([\text{Fe/H}] \) found among samples of Galactic
bulge giants.

Combining these two bulge stars with the results from previous abundance analysis of four other
Galactic bulge dwarfs, all highly magnified by microlensing, gives a mean \([\text{Fe/H}] \) of +0.29 dex for
the six microlensed dwarfs, which rises to +0.41 when the lowest metallicity dwarf, which is actually
a subgiant with \([\text{Fe/H}] \) very discrepant from the other five stars, is removed. On the other hand,
the many large surveys of the metallicity distribution function in the Galactic bulge carried out
at the VLT (Lecureur et al. 2007; Zoccali et al. 2008) and at Keck (Fulbright, McWilliam & Rich 2006; Rich, Origlia & Valenti 2007, among others) from samples of cool, luminous bulge giants give mean \([\text{Fe/H}] \sim -0.1\) dex. This implies that there is an inconsistency between the Fe-metallicity distribution of the microlensed bulge dwarfs and that derived by the bulge giants. This difference is highly statistically significant assuming that both the abundance analyses of the giant samples and of the six microlensed dwarfs have been carried out correctly.

We provide statistical arguments suggesting that to produce consistency a substantial systematic error in the absolute metallicity of Fe in one or both of the two cases, bulge dwarfs vs bulge giants, is necessary. The required offset which must act to either underestimate the metallicities for the giants or overestimate those of the microlensed dwarfs, or both of these, is 0.2 dex in \([\text{Fe/H}]\), ignoring a radial gradient, which would only increase this value. Were a systematic offset of this size present, the probability of the observed metallicity distribution functions for these two groups of bulge stars in very different evolutionary phases to be identical would rise to 15%.

Since the microlensed main sequence region stars are usually analyzed differentially with respect to the Sun, to which they are fairly close in stellar parameters, the resulting systematic errors should be small. Furthermore there are now multiple independent analyses for several of the microlensed dwarfs (see, e.g. Bensby et al. 2009), and there are several major independent surveys of bulge giants, suggesting that it is unlikely that either the dwarfs or the giants or both have major systematic errors in their \([\text{Fe/H}]\) determinations. The contamination by foreground disk stars is predicted to be small for the giant samples; samples of bulge dwarfs selected through microlensing should contain a considerably smaller fraction of foreground disk stars.

A number of mechanisms for producing this difference are discussed, but none seems compelling. We clearly need a still larger sample of microlensed bulge dwarfs to refine the systematic offset required to achieve statistically identical Fe-metallicity distributions and to eliminate completely the possibility that a systematic error of the required size may have occurred in one or both of the Fe-metallicities between the bulge giants and the bulge microlensed dwarfs before indulging in further speculations of the cause of this discrepancy. The rising interest in time-domain phenomena has led to increased attention on how to handle these phenomena efficiently at large telescopes, increasing sensitivity for the handling of targets of opportunity. In the past three years, high dispersion spectra for six highly microlensed bulge dwarfs have been obtained at the Las Campanas or the Keck Observatory. With high hopes that the same will hold for the next three years, we eagerly await future larger samples of microlensed bulge turnoff region stars.

J.G.C. and W.H. are grateful to NSF grant AST-0507219 to JGC for partial support. I.B.T. is grateful for support NSF grant AST-0507325. A.G. was supported by NSF grant 0757888. T. Sumi is grateful for a Grant-in-Aid for Young Scientists (B) and Grant-in-Aid for Scientific Research on Priority Areas, “Development of Extra-solar Planetary Science” by the Ministry of Education, Culture, Sports, and Technology (MEXT) of Japan. I.Bond is grateful to support from the Marsden Fund of the Royal Society of New Zealand.
REFERENCES

Bensby, T., Feltzing, S., Lundstrom, I. & Ilyin, I., 2005, A&A, 433, 185

Bensby, T. et al., 2009, A&A, in press

Bernstein, R., Shectman, S. A., Gunnels, S. M., Mochnacki, S. & Athey, A. E., 2003, SPIE, 4841, Instrument Design and Performance for Optical/Infrared Ground-Based Telescopes, ed. I. Masanori & A. Moorhead, 1694

Biazzo, K., Frasca, A., Catalano S. & Marilli E., 2007, Astr. Nach., 328, 938

Boesgaard, A. M., Jensen, E. E. C. & Deliyannis, C., 2009, AJ, 137, 4949

Castelli, F. & Kurucz, R. L., 2003, in Poster Paper A20, on CD from IAU Sym. 210, Modeling of Stellar Atmospheres, ed. N. E. Piskunov, W. W. Weiss & D. G. Gray (San Francisco: ASP) (see astro-ph/0405087)

Clarkson, W. et al., 2009, ApJ, 684, 1110

Cohen, J. G., Gratton, R. G., Behr, B. & Carretta, E., 1999, ApJ, 523, 739

Cohen, J. G., Huang, W., Udalski, A., Gould, A. & Johnson, J. A., 2008, ApJ, 682, 1029

Cunha, K. & Smith, V. V., 2006, ApJ, 651, 491

Dotter, A., Chaboyer, B., Jevermovic, D., Kostov, V., Baron, E. & Ferguson, J. W., 2008, ApJS, 178, 89

Feltzing, S. & Gilmore, G., 2000, A&A, 355, 949

Figer, D. F. et al, 2002, ApJ, 581, 258

Fulbright, J. P., McWilliam, A. & Rich, R. M., 2006, ApJ, 636, 821

Fulbright, J. P., McWilliam, A. & Rich, R. M., 2007, ApJ, 661, 1162

Gray, D.F. & Johanson, H. L., 1991, ApJ, 103, 439

Grenon, M., 1999, Astrophysics and Space Science, 265, 331

Holmberg, J., Flynn, C. & Portinari, L., 2006, MNRAS, 367, 449

Johnson, J. A., Gal-Yam, A., Leonard, D. C., Simon, J. D., Udalski, A. & Gould, A., 2007, ApJ, 655, L3

Johnson, J. A., Gaido. B.S., Sumi, T., Bond, I. A. & Gould, A., 2008, ApJ, 685, 508

Kurucz, R. L., 1993, ATLAS9 Stellar Atmosphere Programs and 2 km/s Grid, (Kurucz CD-ROM No. 13)
Lecureur, A., Hill, V., Zoccali, M., Barbuy, B., Gomez, A., Minitti, D., Ortolani, S. & Renzini, A., 2007, A&A, 465, 799

Luck, R. E., Kovtyukh, V. V. & Andrievsky, S. M., 2006, AJ, 132, 902

Mashonkina, L., Gehren, T., Travaglio, C., Borkova, T., 2004, A&A, 433, 185

Pasquini, L., Randich, S., Zoccali, M., Hill, V., Charbonnel, C. & Nordstrom, B., 2004, A&A, 424, 951

Pompeia, L., Barbuy, B. & Grenon, M., 2002, ApJ, 566, 845

Reddy, B. E., Tomkink, J., Lambert D. L. & Allende Prieto, C., 2003, MNRAS, 340, 304

Rich, R. M. & Origlia, L., 2005, ApJ, 634, 1293

Rich, R. M., Origlia, L. & Valenti, E., 2007, ApJ, 665, L119

Santos, N. C., Lovis, C., Pace, G., Melendez, J. & Naef, D., 2009, A&A, 493, 309

Sneden, C., 1973, Ph.D. thesis, Univ. of Texas

Zoccali, M. et al., 2003, A&A, 399, 931

Zoccali, M., Hill, V., Lecureur, A., Barbuy, B., Renzini, A., Minitti, D., Gomez, A. & Ortolani, S., 2008, A&A, 486, 177

This preprint was prepared with the AAS L\TeX macros v5.2.
Table 1. Properties of MOA–2008–BLG–310S and MOA–2008–BLG–311S

| ID                | Date of Obs. | Exp. Time (sec.) | Spec. Res | SNR^a | \(v_r\)^b (km s\(^{-1}\)) | Age^c (Gyr) |
|-------------------|--------------|------------------|-----------|-------|---------------------------|-------------|
| MOA–2008–BLG–310S | 8/7/2008     | 4x1800           | 41,000    | 115   | +77.5 ± 2.0               | 9.5±2.0     |
| MOA–2008–BLG–311S | 7/7/2008     | 4x1800           | 29,000    | 104   | -34.1 ± 2.5               | 7.8±2.5     |

^a Signal-to-noise ratio per spectral resolution element in continuum at 6025 Å (at the center of an echelle order).

^b Heliocentric radial velocity.

^c We use isochrones from the Dartmouth Stellar Evolution Database of Dotter et al. (2008), see Fig. 1.

Table 2. Stellar Parameters of MOA–2008–BLG–310S and MOA–2008–BLG–311S

| ID                | \(T_{\text{eff}}\) (K) | \(\log(g)\) (dex) | [Fe/H] (dex) | \(v_r\) (km s\(^{-1}\)) | \(\Delta[X/Fe]/\Delta(EP)^a\) | \(\Delta[X/Fe]/\Delta[W_{\lambda}/\lambda]\) (dex) | \(\Delta[X/Fe]/\Delta\lambda\) \((10^{-4} \text{ dex/Å})\) |
|-------------------|-----------------------|------------------|-------------|-----------------|----------------|--------------------------------|----------------|
| MOA–2008–BLG–310S | 5620                  | 4.3              | +0.5        | 1.0             | 0.013          | -0.055                        | 0.256          |
| MOA–2008–BLG–311S | 5680                  | 4.1              | +0.3        | 1.2             | 0.006          | 0.054                         | -0.066         |

^a Typical range of EP is 4 eV. This slope decreases by ∼0.05 dex/eV for an increase in \(T_{\text{eff}}\) of 250 K.

Table 3. Determinations of \(T_{\text{eff}}\) Using Various Methods For MOA–2008–BLG–310S and MOA–2008–BLG–311S

| ID                | \(T_{\text{eff}}\) \(\text{(K)}\) | \((V-I)_0\) | \(\text{Fe I Lines}\) | \(\text{H}_\alpha\) Profile |
|-------------------|----------------------------------|------------|-------------------------|-----------------------------|
| MOA–2008–BLG–310S | 5620 ±100                        | 5800 ±225^a | 5500 ±150               | ...                         |
| MOA–2008–BLG–311S | 5680 ±100                        | 5640 ±225^a | ...                     | ...                         |

^a We assume an uncertainty of 0.05 mag in \((V-I)_0\) due to uncertainty in the color of the red clump and possible differential reddening between the clump and these particular stars.
Table 4. $W_\lambda$ for the Sample EMP Stars From the HES

| $\lambda$ (Å) | Species | EP (eV) | log($gf$) | MOA–2008–BLG–310S (mÅ) | MOA–2008–BLG–311S (mÅ) |
|---------------|---------|---------|-----------|-------------------------|-------------------------|
| 6300.30       | O(OH)  | 0.00    | −9.780    | 7.1                     | 44.7                    |
| 7771.94       | O(OH)  | 9.15    | 0.369     | 75.4                    | 88.2                    |
| 7774.17       | O(OH)  | 9.15    | 0.223     | 68.2                    | 83.4                    |
| 7775.39       | O(OH)  | 9.15    | 0.001     | 54.0                    | 63.3                    |
| 5682.63       | Na I   | 2.10    | −0.700    | 161.0                   | 159.4                   |
| 5688.19       | Na I   | 2.10    | −0.420    | 167.7                   | 163.8                   |
| 6154.23       | Na I   | 2.10    | −1.530    | 76.5                    | 54.1                    |
| 6160.75       | Na I   | 2.00    | −1.230    | 87.6                    | 85.6                    |
| 5711.09       | Mg I   | 4.34    | −1.670    | 135.0                   | 121.4                   |
| 6318.72       | Mg I   | 5.11    | −2.100    | 80.3                    | ...                     |
| 6319.24       | Mg I   | 5.11    | −2.320    | 60.0                    | ...                     |
| 6696.02       | Al I   | 3.14    | −1.340    | 77.9                    | 73.2                    |
| 6698.67       | Al I   | 3.14    | −1.640    | 46.0                    | 32.3                    |
| 5421.18       | Si I   | 5.62    | −1.430    | ...                     | 85.3                    |
| 5665.55       | Si I   | 4.92    | −2.040    | 74.2                    | 63.9                    |
| 5690.43       | Si I   | 4.93    | −1.870    | 66.8                    | 74.1                    |
| 5701.10       | Si I   | 4.93    | −2.050    | 59.4                    | 53.0                    |
| 5772.15       | Si I   | 5.08    | −1.750    | 81.4                    | 90.0                    |
| 5793.07       | Si I   | 4.93    | −2.060    | 70.6                    | 66.0                    |
| 5948.54       | Si I   | 5.08    | −1.230    | 117.3                   | 113.6                   |
| 6145.02       | Si I   | 5.61    | −1.440    | 61.3                    | 59.1                    |
| 6155.13       | Si I   | 5.62    | −0.760    | 132.5                   | 99.9                    |
| 6237.32       | Si I   | 5.62    | −1.010    | 100.3                   | 98.0                    |
| 6721.84       | Si I   | 5.86    | −0.939    | 78.3                    | 77.4                    |
| 7003.57       | Si I   | 5.96    | −0.830    | 83.0                    | 87.3                    |
| 7005.89       | Si I   | 5.98    | −0.730    | 130.0                   | 106.7                   |
| 7034.90       | Si I   | 5.87    | −0.880    | 97.0                    | 96.7                    |
| 7405.77       | Si I   | 5.61    | −0.820    | 115.8                   | 119.7                   |
| 7415.95       | Si I   | 5.61    | −0.730    | ...                    | 119.6                   |
| 7423.50       | Si I   | 5.62    | −0.580    | ...                    | 135.1                   |
| 7698.97       | K I    | 0.00    | −0.168    | 180.0                   | 172.1                   |
| 5512.99       | Ca I   | 2.93    | −0.300    | 108.0                   | 109.6                   |
| $\lambda$ (Å) | Species | EP (eV) | log($gf$) | MOA–2008–BLG–310S (mÅ) | MOA–2008–BLG–311S (mÅ) |
|---------------|---------|---------|-----------|-------------------------|-------------------------|
| 5581.96       | Ca I    | 2.52    | 0.71      | 117.3                   | 113.5                   |
| 5590.11       | Ca I    | 2.52    | 0.70      | 112.2                   | 110.8                   |
| 5587.45       | Ca I    | 2.93    | 0.20      | ...                     | 148.9                   |
| 6161.30       | Ca I    | 2.52    | 1.03      | 80.0                    | 75.2                    |
| 6166.44       | Ca I    | 2.52    | 0.90      | 98.6                    | 83.8                    |
| 6169.04       | Ca I    | 2.52    | 0.54      | 115.7                   | 114.1                   |
| 6169.56       | Ca I    | 2.52    | 0.27      | ...                     | 134.3                   |
| 6471.66       | Ca I    | 2.52    | 0.59      | 117.9                   | 108.8                   |
| 6493.78       | Ca I    | 2.52    | 1.14      | ...                     | 154.4                   |
| 6499.65       | Ca I    | 2.54    | 0.59      | 108.9                   | 98.7                    |
| 6508.85       | Ca I    | 2.52    | 2.12      | ...                     | 27.2                    |
| 6717.68       | Ca I    | 2.71    | 0.61      | ...                     | 152.3                   |
| 7148.15       | Ca I    | 2.71    | 0.21      | ...                     | 169.0                   |
| 5526.79       | Sc II   | 1.77    | 0.13      | 86.0                    | 92.3                    |
| 5657.90       | Sc II   | 1.51    | 0.50      | 89.2                    | 79.0                    |
| 5667.15       | Sc II   | 1.50    | 1.24      | 66.7                    | 58.2                    |
| 5669.04       | Sc II   | 1.50    | 1.12      | 60.5                    | 56.2                    |
| 5684.20       | Sc II   | 1.51    | 1.08      | 57.1                    | ...                     |
| 5625.64       | Sc II   | 1.51    | 1.13      | 57.7                    | 50.8                    |
| 6604.60       | Sc II   | 1.36    | 1.31      | 60.3                    | 55.1                    |
| 5022.87       | Ti I    | 0.83    | 0.43      | 98.4                    | 100.4                   |
| 5039.96       | Ti I    | 0.02    | 1.13      | 107.0                   | 106.0                   |
| 5210.39       | Ti I    | 0.05    | 0.88      | 102.8                   | ...                     |
| 5426.26       | Ti I    | 0.02    | 3.01      | 13.5                    | ...                     |
| 5471.20       | Ti I    | 1.44    | 1.39      | 17.0                    | ...                     |
| 5490.15       | Ti I    | 1.46    | 0.93      | 45.1                    | ...                     |
| 5648.57       | Ti I    | 2.49    | 0.25      | 33.3                    | ...                     |
| 5662.16       | Ti I    | 2.32    | 0.10      | 46.8                    | ...                     |
| 5689.49       | Ti I    | 2.30    | 0.46      | 31.4                    | 25.6                    |
| 5702.69       | Ti I    | 2.29    | 0.57      | 17.2                    | ...                     |
| 5739.46       | Ti I    | 2.25    | 0.60      | 16.9                    | ...                     |
| 5739.98       | Ti I    | 2.24    | 0.67      | 13.5                    | ...                     |
| $\lambda$ (Å) | Species | EP (eV) | log($gf$) | MOA–2008–BLG–310S (mA) | MOA–2008–BLG–311S (mA) |
|-------------|---------|---------|---------|----------------|----------------|
| 5766.33     | Ti I    | 3.29    | 0.360   | 27.6           | ...            |
| 5866.45     | Ti I    | 1.07    | −0.840  | 77.6           | 63.6           |
| 5880.27     | Ti I    | 1.05    | −2.050  | 18.4           | ...            |
| 5903.32     | Ti I    | 1.07    | −2.140  | 14.3           | ...            |
| 5922.11     | Ti I    | 1.05    | −1.470  | 45.5           | 46.9           |
| 5937.81     | Ti I    | 1.07    | −1.890  | 22.0           | ...            |
| 5941.75     | Ti I    | 1.05    | −1.520  | 45.9           | ...            |
| 5953.16     | Ti I    | 1.89    | −0.329  | ...            | 52.7           |
| 5965.83     | Ti I    | 1.88    | −0.409  | 62.5           | 52.5           |
| 5978.54     | Ti I    | 1.87    | −0.496  | 54.0           | 27.4           |
| 6064.63     | Ti I    | 1.05    | −1.940  | 25.5           | 26.6           |
| 6091.17     | Ti I    | 2.27    | −0.423  | 32.8           | 23.4           |
| 6092.80     | Ti I    | 1.89    | −1.380  | 9.7            | ...            |
| 6126.22     | Ti I    | 1.07    | −1.420  | 46.6           | 33.6           |
| 6258.10     | Ti I    | 1.44    | −0.355  | 76.4           | 72.1           |
| 6258.71     | Ti I    | 1.46    | −0.240  | ...            | 103.9          |
| 6261.10     | Ti I    | 1.43    | −0.479  | 82.9           | 68.0           |
| 6303.76     | Ti I    | 1.44    | −1.570  | 23.0           | ...            |
| 6312.22     | Ti I    | 1.46    | −1.550  | 22.9           | ...            |
| 6743.12     | Ti I    | 0.90    | −1.630  | 50.6           | 27.5           |
| 7138.90     | Ti I    | 1.44    | −1.590  | 18.3           | ...            |
| 7344.69     | Ti I    | 1.46    | −0.992  | ...            | 43.1           |
| 5185.91     | Ti II   | 1.89    | −1.460  | 75.0           | 95.5           |
| 5336.79     | Ti II   | 1.58    | −1.630  | 83.8           | 86.3           |
| 5670.85     | V I     | 1.08    | −0.425  | 52.2           | 35.0           |
| 5703.57     | V I     | 1.05    | −0.212  | 65.8           | 65.0           |
| 6081.44     | V I     | 1.05    | −0.579  | 41.4           | 29.5           |
| 6090.22     | V I     | 1.08    | −0.062  | 67.4           | 47.2           |
| 6199.20     | V I     | 0.29    | −1.280  | 38.2           | 22.7           |
| 6243.10     | V I     | 0.30    | −0.978  | 79.6           | 53.4           |
| 6251.82     | V I     | 0.29    | −1.340  | 43.0           | 25.5           |
| 6274.64     | V I     | 0.27    | −1.670  | 23.6           | ...            |
| $\lambda$ (Å) | Species | EP (eV) | log($gf$) | MOA–2008–BLG–310S (mA) | MOA–2008–BLG–311S (mA) |
|---------------|---------|---------|-----------|-------------------------|-------------------------|
| 6285.14       | V I     | 0.28    | −1.510    | 37.0                    | 23.1                    |
| 5345.81       | Cr I    | 1.00    | −0.970    | …                       | 144.3                   |
| 5348.33       | Cr I    | 1.00    | −1.290    | …                       | 124.0                   |
| 5702.32       | Cr I    | 3.45    | −0.667    | 43.8                    | 36.2                    |
| 5783.09       | Cr I    | 3.32    | −0.500    | 62.5                    | 51.5                    |
| 5783.89       | Cr I    | 3.32    | −0.295    | 79.0                    | 52.5                    |
| 5787.96       | Cr I    | 3.32    | −0.083    | 69.0                    | 64.0                    |
| 6979.80       | Cr I    | 3.46    | −0.411    | 62.0                    | 56.4                    |
| 5537.74       | Mn I    | 2.19    | −2.020    | 82.6                    | 51.3                    |
| 6021.80       | Mn I    | 3.08    | 0.034     | 125.9                   | 119.7                   |
| 5198.72       | Fe I    | 2.22    | −2.140    | 118.6                   | 109.4                   |
| 5406.78       | Fe I    | 4.37    | −1.620    | 49.9                    | 49.2                    |
| 5409.14       | Fe I    | 4.37    | −1.200    | 85.8                    | 65.6                    |
| 5417.04       | Fe I    | 4.41    | −1.580    | 52.9                    | 49.8                    |
| 5441.33       | Fe I    | 4.10    | −1.630    | 50.2                    | 43.4                    |
| 5466.39       | Fe I    | 4.37    | −0.620    | …                       | 122.7                   |
| 5473.90       | Fe I    | 4.15    | −0.690    | …                       | 86.7                    |
| 5487.14       | Fe I    | 4.41    | −1.430    | 64.2                    | …                       |
| 5494.46       | Fe I    | 4.07    | −1.990    | 49.3                    | …                       |
| 5522.45       | Fe I    | 4.21    | −1.450    | 62.8                    | 56.0                    |
| 5525.55       | Fe I    | 4.23    | −1.080    | 82.6                    | 73.1                    |
| 5539.29       | Fe I    | 3.64    | −2.590    | 41.3                    | …                       |
| 5554.88       | Fe I    | 4.55    | −0.350    | 116.4                   | 127.3                   |
| 5560.21       | Fe I    | 4.43    | −1.100    | 71.8                    | 69.3                    |
| 5567.39       | Fe I    | 2.61    | −2.670    | …                       | 85.6                    |
| 5568.87       | Fe I    | 3.63    | −2.850    | 25.0                    | …                       |
| 5579.34       | Fe I    | 4.23    | −2.320    | 25.4                    | …                       |
| 5618.63       | Fe I    | 4.21    | −1.630    | 65.6                    | 62.9                    |
| 5619.59       | Fe I    | 4.39    | −1.530    | 63.0                    | 45.5                    |
| 5620.49       | Fe I    | 4.15    | −1.810    | …                       | 59.9                    |
| 5624.04       | Fe I    | 4.39    | −1.220    | 76.9                    | 73.9                    |
| 5641.44       | Fe I    | 4.26    | −1.080    | …                       | 71.9                    |
Table 4—Continued

| $\lambda$ (Å) | Species | EP (eV) | log($gf$) | MOA–2008–BLG–310S (mA) | MOA–2008–BLG–311S (mA) |
|---------------|---------|---------|-----------|------------------------|------------------------|
| 5650.02       | Fe I    | 5.10    | $-0.820$  | 69.5                   | ...                    |
| 5652.32       | Fe I    | 4.26    | $-1.850$  | 41.2                   | 32.0                   |
| 5653.89       | Fe I    | 4.39    | $-1.540$  | 52.3                   | 46.0                   |
| 5661.35       | Fe I    | 4.28    | $-1.760$  | 46.4                   | ...                    |
| 5662.52       | Fe I    | 4.18    | $-0.570$  | 115.6                  | 123.0                  |
| 5667.52       | Fe I    | 4.48    | $-1.500$  | 72.1                   | ...                    |
| 5679.02       | Fe I    | 4.65    | $-0.820$  | 77.6                   | 63.0                   |
| 5680.24       | Fe I    | 4.19    | $-2.480$  | 25.3                   | 12.4                   |
| 5701.54       | Fe I    | 2.56    | $-2.140$  | 107.9                  | 95.8                   |
| 5705.47       | Fe I    | 4.30    | $-1.360$  | 61.0                   | 47.7                   |
| 5731.76       | Fe I    | 4.26    | $-1.200$  | 80.2                   | 72.7                   |
| 5741.85       | Fe I    | 4.26    | $-1.850$  | 57.0                   | ...                    |
| 5752.04       | Fe I    | 4.55    | $-0.940$  | 78.1                   | 81.3                   |
| 5753.12       | Fe I    | 4.26    | $-0.690$  | 101.1                  | 106.6                  |
| 5760.35       | Fe I    | 3.64    | $-2.390$  | 40.8                   | 30.6                   |
| 5762.42       | Fe I    | 3.64    | $-2.180$  | ...                    | 44.1                   |
| 5775.06       | Fe I    | 4.22    | $-1.300$  | 80.8                   | 77.0                   |
| 5778.46       | Fe I    | 2.59    | $-3.430$  | 43.0                   | ...                    |
| 5793.91       | Fe I    | 4.22    | $-1.600$  | 55.7                   | 52.6                   |
| 5805.76       | Fe I    | 5.03    | $-1.490$  | 26.2                   | 23.4                   |
| 5806.72       | Fe I    | 4.61    | $-0.950$  | 82.4                   | 70.8                   |
| 5807.78       | Fe I    | 3.29    | $-3.350$  | 23.5                   | ...                    |
| 5827.88       | Fe I    | 3.28    | $-3.310$  | 26.2                   | 18.5                   |
| 5852.22       | Fe I    | 4.55    | $-1.230$  | 58.6                   | 57.0                   |
| 5855.09       | Fe I    | 4.61    | $-1.480$  | 39.9                   | 35.5                   |
| 5856.08       | Fe I    | 4.29    | $-1.330$  | 55.4                   | 48.3                   |
| 5859.60       | Fe I    | 4.55    | $-0.550$  | 89.8                   | 85.6                   |
| 5862.35       | Fe I    | 4.55    | $-0.330$  | 113.2                  | 102.7                  |
| 5873.21       | Fe I    | 4.26    | $-2.040$  | 41.1                   | ...                    |
| 5881.28       | Fe I    | 4.61    | $-1.740$  | 30.2                   | 30.1                   |
| 5883.81       | Fe I    | 3.96    | $-1.260$  | 88.7                   | 79.5                   |
| 5927.79       | Fe I    | 4.65    | $-0.990$  | 58.4                   | 49.4                   |
### Table 4—Continued

| $\lambda$ (Å) | Species | EP (eV) | log($gf$) | MOA–2008–BLG–310S (mA) | MOA–2008–BLG–311S (mA) |
|---------------|---------|---------|-----------|------------------------|------------------------|
| 5929.67       | Fe I    | 4.55    | −1.310    | 60.8                   | 33.5                   |
| 5930.17       | Fe I    | 4.65    | −0.140    | 112.7                  | 111.1                  |
| 5934.65       | Fe I    | 3.93    | −1.070    | 97.0                   | 86.9                   |
| 5940.99       | Fe I    | 4.18    | −2.050    | 34.3                   | 40.1                   |
| 5952.72       | Fe I    | 3.98    | −1.340    | 92.2                   | 90.6                   |
| 5956.69       | Fe I    | 0.86    | −4.500    | 73.8                   | 77.6                   |
| 5976.79       | Fe I    | 3.94    | −1.330    | 89.8                   | 81.4                   |
| 5983.69       | Fe I    | 4.55    | −0.660    | 89.3                   | 89.4                   |
| 5984.83       | Fe I    | 4.73    | −0.260    | 111.1                  | 105.5                  |
| 6024.05       | Fe I    | 4.55    | 0.030     | …                      | 125.9                  |
| 6027.05       | Fe I    | 4.07    | −1.090    | 82.6                   | 76.9                   |
| 6055.99       | Fe I    | 4.73    | −0.370    | 92.4                   | 86.4                   |
| 6078.50       | Fe I    | 4.79    | −0.330    | 105.0                  | 106.1                  |
| 6079.00       | Fe I    | 4.65    | −1.020    | 66.4                   | 56.0                   |
| 6089.57       | Fe I    | 5.02    | −0.900    | 57.5                   | 54.3                   |
| 6093.67       | Fe I    | 4.61    | −1.400    | 50.6                   | 45.0                   |
| 6094.37       | Fe I    | 4.65    | −1.840    | 38.1                   | 24.9                   |
| 6096.66       | Fe I    | 3.98    | −1.830    | 59.5                   | 54.5                   |
| 6151.62       | Fe I    | 2.18    | −3.370    | 72.2                   | 81.2                   |
| 6157.73       | Fe I    | 4.07    | −1.160    | 89.3                   | 70.2                   |
| 6159.37       | Fe I    | 4.61    | −1.920    | 24.9                   | …                      |
| 6165.36       | Fe I    | 4.14    | −1.470    | 65.0                   | 57.7                   |
| 6173.34       | Fe I    | 2.22    | −2.880    | 93.6                   | 77.7                   |
| 6180.20       | Fe I    | 2.73    | −2.650    | 91.6                   | 84.0                   |
| 6187.99       | Fe I    | 3.94    | −1.620    | 66.2                   | 72.5                   |
| 6200.31       | Fe I    | 2.61    | −2.370    | 97.2                   | 98.0                   |
| 6240.65       | Fe I    | 2.22    | −3.170    | 70.8                   | 65.2                   |
| 6265.13       | Fe I    | 2.18    | −2.540    | 114.9                  | 108.1                  |
| 6271.28       | Fe I    | 3.33    | −2.700    | 50.3                   | …                      |
| 6297.79       | Fe I    | 2.22    | −2.640    | 99.7                   | …                      |
| 6302.50       | Fe I    | 3.69    | −1.110    | 116.2                  | 104.3                  |
| 6315.81       | Fe I    | 4.07    | −1.610    | 65.0                   | 48.5                   |
Table 4—Continued

| $\lambda$ (Å) | Species | EP (eV) | log($gf$) | MOA–2008–BLG–310S (mA) | MOA–2008–BLG–311S (mA) |
|----------------|---------|---------|-----------|--------------------------|--------------------------|
| 6355.03        | Fe I    | 2.84    | −2.290    | ...                      | 93.8                     |
| 6380.75        | Fe I    | 4.19    | −1.380    | 74.3                     | 70.1                     |
| 6392.54        | Fe I    | 2.28    | −3.990    | 32.2                     | 42.2                     |
| 6408.03        | Fe I    | 3.69    | −1.020    | ...                      | 113.9                    |
| 6469.21        | Fe I    | 4.83    | −0.730    | 84.3                     | 80.8                     |
| 6475.63        | Fe I    | 2.56    | −2.940    | 90.2                     | 75.5                     |
| 6481.87        | Fe I    | 2.28    | −3.010    | 87.5                     | 93.3                     |
| 6495.74        | Fe I    | 4.83    | −0.840    | 67.7                     | 67.5                     |
| 6498.94        | Fe I    | 0.96    | −4.690    | 74.1                     | 58.0                     |
| 6533.93        | Fe I    | 4.56    | −1.360    | 59.2                     | 54.6                     |
| 6546.24        | Fe I    | 2.76    | −1.540    | 129.6                    | 126.1                    |
| 6581.21        | Fe I    | 1.48    | −4.680    | 51.9                     | 31.8                     |
| 6593.87        | Fe I    | 2.43    | −2.370    | 114.5                    | 107.1                    |
| 6597.56        | Fe I    | 4.79    | −0.970    | 65.2                     | 61.3                     |
| 6608.02        | Fe I    | 2.28    | −3.930    | 40.2                     | 24.2                     |
| 6609.11        | Fe I    | 2.56    | −2.660    | 94.6                     | 92.3                     |
| 6625.02        | Fe I    | 1.01    | −5.370    | 44.1                     | 29.9                     |
| 6627.54        | Fe I    | 4.55    | −1.580    | 48.7                     | 40.0                     |
| 6646.93        | Fe I    | 2.61    | −3.960    | 28.1                     | ...                      |
| 6648.12        | Fe I    | 1.01    | −5.920    | 19.9                     | 17.6                     |
| 6703.57        | Fe I    | 2.76    | −3.060    | 56.2                     | 49.7                     |
| 6713.77        | Fe I    | 4.79    | −1.500    | 35.6                     | 27.7                     |
| 6715.38        | Fe I    | 4.61    | −1.540    | 56.3                     | 45.6                     |
| 6716.22        | Fe I    | 4.58    | −1.850    | 35.9                     | 31.9                     |
| 6725.35        | Fe I    | 4.19    | −2.250    | 32.0                     | 34.3                     |
| 6726.67        | Fe I    | 4.61    | −1.070    | 66.3                     | 60.8                     |
| 6733.15        | Fe I    | 4.64    | −1.480    | 47.4                     | 48.5                     |
| 6739.52        | Fe I    | 1.56    | −4.790    | 26.4                     | ...                      |
| 6746.95        | Fe I    | 2.61    | −4.300    | 12.5                     | ...                      |
| 6750.15        | Fe I    | 2.42    | −2.580    | 99.3                     | 93.0                     |
| 6752.71        | Fe I    | 4.64    | −1.200    | 59.9                     | 47.8                     |
| 6786.86        | Fe I    | 4.19    | −1.970    | 57.1                     | ...                      |
Table 4—Continued

| λ (Å) | Species | EP (eV) | log($gf$) | MOA–2008–BLG–310S (mÅ) | MOA–2008–BLG–311S (mÅ) |
|-------|---------|---------|-----------|------------------------|------------------------|
| 6837.02 | Fe I | 4.59 | −1.690 | 32.5 | 27.3 |
| 6839.83 | Fe I | 2.56 | −3.350 | 56.7 | 60.7 |
| 6842.68 | Fe I | 4.64 | −1.220 | 65.8 | 57.3 |
| 6843.65 | Fe I | 4.55 | −0.830 | 84.8 | 74.8 |
| 6855.18 | Fe I | 4.56 | −0.740 | 96.7 | 89.9 |
| 6855.71 | Fe I | 4.61 | −1.780 | 39.9 | 28.4 |
| 6858.15 | Fe I | 4.61 | −0.930 | 70.8 | 72.7 |
| 6861.95 | Fe I | 2.42 | −3.850 | 46.0 | ... |
| 6862.49 | Fe I | 4.56 | −1.470 | 49.8 | 39.1 |
| 6971.93 | Fe I | 3.02 | −3.340 | ... | 20.0 |
| 6978.85 | Fe I | 2.48 | −2.450 | 103.6 | 97.2 |
| 6988.52 | Fe I | 2.40 | −3.560 | 59.4 | 52.6 |
| 6999.88 | Fe I | 4.10 | −1.460 | 76.1 | 73.4 |
| 7000.62 | Fe I | 4.14 | −2.390 | 36.7 | 34.5 |
| 7007.96 | Fe I | 4.18 | −1.960 | 46.6 | 41.5 |
| 7014.98 | Fe I | 2.45 | −4.200 | 17.6 | ... |
| 7022.95 | Fe I | 4.19 | −1.150 | 88.2 | 85.5 |
| 7038.22 | Fe I | 4.22 | −1.200 | 103.5 | 86.7 |
| 7107.46 | Fe I | 4.19 | −2.040 | 49.7 | 41.3 |
| 7112.17 | Fe I | 2.99 | −3.000 | 63.8 | 46.1 |
| 7114.55 | Fe I | 2.69 | −4.000 | 22.7 | ... |
| 7130.92 | Fe I | 4.22 | −0.750 | 125.8 | 113.2 |
| 7132.98 | Fe I | 4.07 | −1.630 | 63.4 | 53.4 |
| 7142.52 | Fe I | 4.95 | −1.030 | 60.9 | 49.9 |
| 7151.47 | Fe I | 2.48 | −3.660 | 59.0 | 39.4 |
| 7181.20 | Fe I | 4.22 | −1.250 | ... | 70.4 |
| 7284.84 | Fe I | 4.14 | −1.700 | 61.0 | ... |
| 7285.27 | Fe I | 4.61 | −1.660 | 42.2 | ... |
| 7306.56 | Fe I | 4.18 | −1.690 | 66.8 | ... |
| 7401.69 | Fe I | 4.19 | −1.350 | 64.0 | 56.6 |
| 7411.16 | Fe I | 4.28 | −0.280 | ... | 121.6 |
| 7418.67 | Fe I | 4.14 | −1.380 | 71.3 | 64.2 |
Table 4—Continued

| λ (Å) | Species | EP (eV) | log(gf) | MOA–2008–BLG–310S (mA) | MOA–2008–BLG–311S (mA) |
|-------|---------|---------|---------|------------------------|------------------------|
| 7440.92 | Fe I    | 4.91    | −0.720  | 84.6                   | 75.7                   |
| 7443.02 | Fe I    | 4.19    | −1.780  | 64.5                   | ...                    |
| 7447.40 | Fe I    | 4.95    | −1.090  | 56.3                   | 43.0                   |
| 7454.00 | Fe I    | 4.19    | −2.370  | 32.4                   | 23.0                   |
| 7461.52 | Fe I    | 2.56    | −3.530  | 54.5                   | 43.3                   |
| 7491.65 | Fe I    | 4.30    | −1.070  | 90.7                   | 81.2                   |
| 7498.53 | Fe I    | 4.14    | −2.220  | 36.7                   | 21.3                   |
| 7568.91 | Fe I    | 4.28    | −0.940  | 102.2                  | 93.8                   |
| 7583.79 | Fe I    | 3.02    | −1.890  | 112.1                  | 101.3                  |
| 7588.31 | Fe I    | 5.03    | −1.210  | 55.0                   | 46.1                   |
| 7751.12 | Fe I    | 4.99    | −0.850  | 73.3                   | 66.8                   |
| 7807.92 | Fe I    | 4.99    | −0.620  | 86.9                   | 78.5                   |
| 5197.58 | Fe II   | 3.23    | −2.230  | 90.3                   | ...                    |
| 5234.63 | Fe II   | 3.22    | −2.220  | 97.5                   | 101.0                  |
| 5414.08 | Fe II   | 3.22    | −3.620  | 39.9                   | ...                    |
| 5425.26 | Fe II   | 3.00    | −3.240  | 58.9                   | 61.5                   |
| 5534.85 | Fe II   | 3.25    | −2.640  | 71.0                   | 88.4                   |
| 5991.38 | Fe II   | 3.15    | −3.570  | 46.5                   | 60.1                   |
| 6084.11 | Fe II   | 3.20    | −3.800  | 28.8                   | 36.0                   |
| 6149.26 | Fe II   | 3.89    | −2.690  | 48.2                   | 48.7                   |
| 6247.56 | Fe II   | 3.89    | −2.360  | 65.2                   | 77.2                   |
| 6369.46 | Fe II   | 2.89    | −4.200  | 28.3                   | 34.2                   |
| 6416.92 | Fe II   | 3.89    | −2.690  | 46.3                   | 48.1                   |
| 6516.08 | Fe II   | 2.89    | −3.450  | 64.6                   | 73.7                   |
| 7449.34 | Fe II   | 3.89    | −3.310  | 37.1                   | 33.0                   |
| 5530.79 | Co I    | 1.71    | −2.060  | 49.8                   | 35.1                   |
| 5647.23 | Co I    | 2.28    | −1.560  | 34.4                   | ...                    |
| 6189.00 | Co I    | 1.71    | −2.450  | 25.3                   | 20.4                   |
| 6632.45 | Co I    | 2.28    | −2.000  | 27.4                   | 12.9                   |
| 7417.41 | Co I    | 2.04    | −2.070  | 29.7                   | 16.9                   |
| 5578.72 | Ni I    | 1.68    | −2.640  | 83.9                   | 66.5                   |
| 5587.86 | Ni I    | 1.93    | −2.140  | ...                   | 75.3                   |
Table 4—Continued

| λ (Å) | Species | EP (eV) | log($gf$) | MOA–2008–BLG–310S (mA) | MOA–2008–BLG–311S (mA) |
|-------|---------|---------|-----------|-------------------------|-------------------------|
| 5589.36 | Ni I | 3.90 | −1.140 | 43.0 | 36.6 |
| 5593.74 | Ni I | 3.90 | −0.840 | 66.4 | 61.2 |
| 5625.32 | Ni I | 4.09 | −0.701 | 61.4 | 52.8 |
| 5682.20 | Ni I | 4.10 | −0.469 | 78.6 | 70.5 |
| 5748.35 | Ni I | 1.68 | −3.260 | … | 38.3 |
| 5760.83 | Ni I | 4.10 | −0.805 | 60.7 | 64.9 |
| 5796.09 | Ni I | 1.95 | −3.690 | 27.3 | … |
| 5805.22 | Ni I | 4.17 | −0.638 | 60.1 | 53.7 |
| 5846.99 | Ni I | 1.68 | −3.210 | 46.4 | 48.0 |
| 6053.69 | Ni I | 4.23 | −1.070 | 41.4 | 42.9 |
| 6086.28 | Ni I | 4.26 | −0.515 | 65.7 | 55.5 |
| 6128.97 | Ni I | 1.68 | −3.330 | 47.3 | 34.3 |
| 6130.13 | Ni I | 4.26 | −0.959 | 41.6 | 36.0 |
| 6175.37 | Ni I | 4.09 | −0.535 | 76.5 | 70.4 |
| 6176.81 | Ni I | 4.09 | −0.529 | 86.0 | 79.4 |
| 6177.24 | Ni I | 1.83 | −3.510 | 38.7 | 30.8 |
| 6186.71 | Ni I | 4.10 | −0.965 | 56.4 | 57.4 |
| 6204.60 | Ni I | 4.09 | −1.140 | 47.0 | 35.8 |
| 6314.66 | Ni I | 1.93 | −1.770 | 114.2 | 99.1 |
| 6360.82 | Ni I | 4.17 | −1.150 | 34.1 | 35.8 |
| 6370.35 | Ni I | 3.54 | −1.940 | … | 25.7 |
| 6378.25 | Ni I | 4.15 | −0.899 | 55.1 | 52.7 |
| 6482.80 | Ni I | 1.93 | −2.630 | 70.2 | 72.8 |
| 6586.31 | Ni I | 1.95 | −2.810 | 69.4 | 63.8 |
| 6598.60 | Ni I | 4.23 | −0.978 | 49.3 | 47.0 |
| 6635.12 | Ni I | 4.42 | −0.828 | … | 34.7 |
| 6643.63 | Ni I | 1.68 | −2.300 | 127.8 | 109.2 |
| 6767.77 | Ni I | 1.83 | −2.170 | 103.7 | 100.8 |
| 6772.31 | Ni I | 3.66 | −0.987 | 68.2 | 74.8 |
| 6842.04 | Ni I | 3.66 | −1.470 | 52.7 | 54.1 |
| 7030.01 | Ni I | 3.54 | −1.730 | 34.7 | 33.6 |
| 7110.88 | Ni I | 1.93 | −2.970 | 80.2 | 59.6 |
Table 4—Continued

| λ (Å) | Species | EP (eV) | log(gf) | MOA–2008–BLG–310S (mA) | MOA–2008–BLG–311S (mA) |
|-------|---------|---------|---------|------------------------|------------------------|
| 7122.20 | Ni I | 3.54 | 0.048 | ... | 142.5 |
| 7414.50 | Ni I | 1.99 | −2.570 | 98.0 | 93.2 |
| 7422.27 | Ni I | 3.63 | −0.129 | 128.7 | 124.4 |
| 7574.05 | Ni I | 3.83 | −0.580 | 92.3 | 88.6 |
| 7727.62 | Ni I | 3.68 | −0.162 | 114.1 | 115.4 |
| 7748.89 | Ni I | 3.70 | −0.130 | 116.7 | 113.5 |
| 7788.93 | Ni I | 1.95 | −2.420 | ... | 119.5 |
| 7797.59 | Ni I | 3.90 | −0.180 | 105.6 | 100.1 |
| 7826.77 | Ni I | 3.70 | −1.950 | 27.7 | 27.7 |
| 5105.54 | Cu I | 1.39 | −1.505 | 138.0 | 124.8 |
| 5782.12 | Cu I | 1.64 | −1.780 | 135.9 | 125.8 |
| 6362.34 | Zn I | 5.79 | 0.140 | 33.0 | 33.5 |
| 5853.70 | Ba II | 0.60 | −1.010 | 76.0 | 62.2 |
| 6141.70 | Ba II | 0.70 | −0.070 | 127.0 | 125.9 |
| 6496.90 | Ba II | 0.60 | −0.380 | 110.5 | 111.1 |
| 4883.69 | Y II | 1.08 | 0.070 | 75.0 | ... |
| 5087.43 | Y II | 1.08 | −0.170 | 65.3 | 48.0 |
| 5200.42 | Y II | 0.99 | −0.570 | 45.0 | ... |
| 6127.44 | Zr I | 0.15 | −1.060 | 8.0 | ... |
| 6134.55 | Zr I | 0.00 | −1.280 | 5.5 | ... |
| 5319.81 | Nd II | 0.55 | −0.140 | 18.0 | ... |
Table 5. Abundances in MOA–2008–BLG–310S

| Species | log\[e(X)\]^a | σ_{obs}^b | Num. of Lines | log[e(X)/e(\text{X})_{\odot}] | [X/Fe]^k | σ_{pred} for [X/Fe] (dex) | Notes |
|---------|----------------|-----------|--------------|----------------|----------|-------------------------|-------|
| C(CH)   | 8.89           | 0.15      | band         | +0.30          | −0.10    | 0.17                    | syn   |
| O I     | 9.09           | 0.16      | 4            | +0.20          | −0.22    | 0.19                    | high χ|
| Na I    | 6.63           | 0.16      | 4            | +0.54          | +0.12    | 0.09                    |       |
| Mg I    | 8.06           | 0.17      | 3            | +0.59          | +0.17    | 0.07                    |       |
| Al I    | 6.72           | 0.15      | 2            | +0.54          | +0.12    | 0.08                    |       |
| Si I    | 8.05           | 0.17      | 15           | +0.52          | +0.10    | 0.17                    | high χ|
| K I     | 5.45           | ⋯         | 1            | +0.22          | −0.20    | 0.12                    |       |
| Ca I    | 6.45           | 0.12      | 8            | +0.34          | −0.08    | 0.07                    |       |
| Sc II   | 3.73           | 0.15      | 6            | +0.50          | +0.08    | 0.10                    | d     |
| Ti I    | 5.31           | 0.13      | 31           | +0.45          | +0.03    | 0.11                    |       |
| Ti II   | 5.32           | 0.04      | 2            | +0.45          | +0.03    | 0.10                    |       |
| V I     | 4.40           | 0.10      | 9            | +0.61          | +0.19    | 0.14                    | d     |
| Cr I    | 6.17           | 0.15      | 5            | +0.51          | +0.09    | 0.07                    |       |
| Mn I    | 5.79           | 0.09      | 2            | +0.42          | +0.00    | 0.11                    | e     |
| Fe I    | 7.90           | 0.14      | 100          | +0.42          | 0.00     | 0.09                    |       |
| Fe II   | 7.87           | 0.14      | 13           | +0.39          | −0.03    | 0.17                    |       |
| Co I    | 5.40           | 0.11      | 5            | +0.63          | +0.19    | 0.08                    | d     |
| Ni I    | 6.74           | 0.15      | 37           | +0.56          | +0.14    | 0.05                    |       |
| Cu I    | 4.78           | 0.20      | 2            | +0.81          | +0.39    | 0.15                    | f     |
| Zn I    | 4.92           | ⋯         | 1            | +0.37          | −0.05    | 0.13                    |       |
| Y II    | 2.59           | 0.15      | 3            | +0.53          | 0.11     | 0.12                    |       |
| Ba II   | 2.60           | 0.04      | 3            | +0.31          | −0.11    | 0.17                    | d     |
| Nd II   | 1.77           | ⋯         | 1            | +0.31          | −0.11    | 0.12                    |       |

^aThis is log[(n(X)/n(H)] + 12.0 dex.

^bRms dispersion about the mean abundance, using differential line-by-line abundances with respect to the Sun.

dThe HFS corrections are small and not an issue.

^eThe HFS corrections are large and are a concern.

^fThe HFS corrections are very large and are a major concern.

^iThe uncertainty in [Fe/H] inferred from the 100 Fe I lines.

^jThe uncertainty in [Fe/H] inferred from the 13 Fe II lines.

^kThe reference species (Fe I or Fe II) is based on the level of excitation and ionization. See Table 4 in Cohen et al. (2008).
### Table 6. Abundances in MOA–2008–BLG–311S

| Species | log$[\epsilon(X)]^a$ (dex) | $\sigma_{obs}^b$ (dex) | Num. of Lines | log$[\epsilon(X)/\epsilon(X)_{\odot}]$ (dex) | [X/Fe]$^k$ colhead (dex) | $\sigma_{pred}$ for [X/Fe] (dex) | Notes |
|---------|-----------------|-----------------|--------------|-----------------|-----------------|-----------------|-------|
| C(CH)   | 8.89            | 0.15            | band         | +0.30           | +0.05           | 0.17            | syn   |
| O I     | 9.31            | 0.12            | 4            | +0.42           | +0.14           | 0.19            | high $\chi$ |
| Na I    | 6.54            | 0.09            | 4            | +0.45           | +0.20           | 0.09            |       |
| Mg I    | 7.91            | 0.14            | 4            | +0.33           | +0.08           | 0.07            |       |
| Al I    | 6.72            | 0.09            | 2            | +0.54           | +0.29           | 0.08            |       |
| Si I    | 7.94            | 0.12            | 15           | +0.41           | +0.16           | 0.17            | high $\chi$ |
| K I     | 5.45            | · · ·            | 1            | +0.22           | -0.03           | 0.12            |       |
| Ca I    | 6.49            | 0.18            | 9            | +0.36           | +0.11           | 0.07            |       |
| Sc II   | 3.47            | 0.11            | 6            | +0.24           | -0.04           | 0.10            | d     |
| Ti I    | 5.25            | 0.18            | 15           | +0.42           | +0.17           | 0.11            |       |
| Ti II   | 5.30            | 0.12            | 2            | +0.43           | +0.15           | 0.10            |       |
| V I     | 4.10            | 0.10            | 8            | +0.31           | +0.06           | 0.14            | d     |
| Cr I    | 5.98            | 0.11            | 6            | +0.32           | +0.07           | 0.07            |       |
| Mn I    | 5.66            | 0.12            | 2            | +0.29           | +0.04           | 0.11            | e     |
| Fe I    | 7.73            | 0.16            | 92           | +0.25           | 0.00            | 0.09$^i$        |       |
| Fe II   | 7.75            | 0.16            | 11           | +0.28           | +0.03           | 0.17$^j$        |       |
| Co I    | 5.14            | 0.08            | 4            | +0.36           | +0.11           | 0.08            | d     |
| Ni I    | 6.60            | 0.15            | 41           | +0.42           | +0.17           | 0.05            |       |
| Cu I    | 4.35            | 0.09            | 2            | +0.38           | +0.13           | 0.15            | f     |
| Zn I    | 4.84            | · · ·            | 1            | +0.29           | +0.04           | 0.13            |       |
| Y II    | 2.34            | · · ·            | 1            | +0.45           | 0.17            | 0.12            |       |
| Ba II   | 2.24            | 0.11            | 3            | +0.12           | -0.13           | 0.17            | d     |

---

$^a$This is log$[\langle n(X)/n(H)\rangle] + 12.0$ dex.

$^b$Rms dispersion about the mean abundance, using differential line-by-line abundances with respect to the Sun.

$^d$The HFS corrections are small and not an issue.

$^e$The HFS corrections are large and are a concern.

$^f$The HFS corrections are very large and are a major concern.

$^i$The uncertainty in [Fe/H] inferred from the 92 Fe I lines.

$^j$The uncertainty in [Fe/H] inferred from the 11 Fe II lines.

$^k$The reference species (Fe I or Fe II) is based on the level of excitation and ionization. See Table 4 in Cohen et al. (2008).
Table 7. Probability for Identical Fe-Metallicity Distributions for the 6 Microlensed Dwarfs and the Bulge Giants

| Systematic Offset$^a$ (dex) | Prob. $<[\text{Fe/H}]>(6$ Dwarfs)$^b$ (%) |
|-----------------------------|------------------------------------------|
| 0.0                         | 0.39                                     |
| −0.05                       | 1.65                                     |
| −0.10                       | 4.94                                     |
| −0.15                       | 11.53                                    |
| −0.20                       | 21.30                                    |

$^a$The systematic offset between the Fe-metallicity scale of Zoccali et al. (2008) and that for the abundances of the 6 microlensed main sequent turnoff region stars in the Galactic bulge.

$^b$The probability of achieving the mean $[\text{Fe/H}]$ for the 6 dwarfs, $+0.29$ dex, from the Zoccali et al. (2008) Fe-metallicity distribution function for Baade’s Window.
Fig. 1.— A CMD with axes $T_{\text{eff}}$ and $M_I$ is shown with the positions of the microlensed bulge dwarfs \text{MOA–2008–BLG–310S} and \text{MOA–2008–BLG–311S} (the fainter of the two) as well as with isochrones from the Dartmouth Stellar Evolution Database (\text{Dotter et al., 2008}) with $[\text{Fe/H}] +0.21$ dex and $[\alpha/\text{Fe}] = 0.0$ dex. The isochrones range in age from 6 to 14 Gyr in 1 Gyr increments.
Fig. 2.— Dependence of deduced abundance [Fe/H] from a weak Fe I line of fixed $W_\lambda$ on $T_{\text{eff}}$ and log($g$) for lines of low ($\chi = 1.0$ eV, small symbols connected by dashed lines) and high ($\chi = 4.8$ eV, large symbols connected by solid lines) excitation potential. Open symbols denote model atmospheres with log($g$) = 4.0 dex, filled symbols denote those with log($g$) = 4.0 dex. The vertical axis is the difference in derived [Fe/H] from the Fe I line with respect to the model with $T_{\text{eff}} = 5500$ K, log($g$) = 4.5 dex, and [Fe/H] solar. Increasing [Fe/H] of the model atmosphere by 0.5 dex increases the deduced [Fe/H] by 0.05 dex. Note the low sensitivity of high $\chi$ Fe I lines to $T_{\text{eff}}$, log($g$), and also to the adopted [Fe/H] for the model.
Fig. 3.— Abundance ratios $[O/Fe]$ (upper panel) and $[Na/Fe]$ (lower panel) are shown as a function of $[Fe/H]$. OGLE–2006–BLG–265S (Johnson et al. 2007), OGLE–2007–BLG–349S (Cohen et al. 2008), MOA–2006–BLG–099S (Johnson et al. 2008), OGLE–2008–BLG–209S (Bensby et al. 2009), and, from the present paper, MOA–2008–BLG–310S and MOA–2008–BLG–311S are shown as large filled circles; error bars are shown for them as well. Samples of bulge M and K giants of Fulbright, McWilliam & Rich (2007) (small filled circles), Rich & Origlia (2005) (small open circles), Lecureur et al. (2007) (small stars), and for M giants in the inner bulge from Rich, Origlia & Valenti (2007) (small open circles) are also shown; their errors are somewhat smaller than those of the microlensed dwarfs.
Fig. 4.— The same as Figure 3 for [Mg/Fe] (upper panel), [Al/Fe] (middle panel) and [Si/Fe] (lower panel). The symbols are the same as in Figure 3.
Fig. 5.— The same as Figure 3 for [Ca/Fe] (upper panel) and for [Ti/Fe] (lower panel). The symbols are the same as in Figure 3.
Fig. 6.— The distribution in Galactic latitude and longitude of the six microlensed bulge stars. The heliocentric radial velocity for each star is indicated by an arrow, upward being positive, with a scale of 70 km s\(^{-1}\) per degree. The small open circle denotes the unpublished spectrum of OGLE–2007–BLG–514 taken by M. Rauch being analyzed by C. Epstein. Baade’s Window is marked by the filled rectangle, and its Galactocentric radius is indicated by a circle.
The Fe-metallicity distribution from Zoccali et al. (2008) for stars in Baade’s Window is shown. The 6 microlensed dwarfs with high resolution spectra and detailed abundance analyses, including the two published here, are shown as filled circles: see Cohen et al. (2008) for OGLE–2007–BLG–349S, Johnson et al. (2007) for OGLE–2006–BLG–265S, Johnson et al. (2008) for MOA–2006–BLG–099S, and Bensby et al. (2009) for OGLE–2008-BLG–209S for the other four stars. A typical uncertainty in [Fe/H] for the microlensed bulge dwarfs is shown for the most metal-rich star.