

CLUES TO THE METALLICITY DISTRIBUTION IN THE GALACTIC BULGE: ABUNDANCES IN OGLE-2007-BLG-349S¹

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ABSTRACT

We present an abundance analysis based on high-dispersion and high signal-to-noise ratio Keck spectra of a very highly microlensed Galactic bulge dwarf, OGLE-2007-BLG-349S, with $T_{\text{eff}} \sim 5400$ K. The amplification at the time the spectra were taken ranged from 350 to 450. This bulge star is highly enhanced in metallicity with $[\text{Fe}/\text{H}] = +0.51 \pm 0.09$ dex. The abundance ratios for the 28 species of 26 elements for which features could be detected in the spectra are almost all solar. In particular, there is no evidence for enhancement of any of the α -elements, including O and Mg. We conclude that the high $[\text{Fe}/\text{H}]$ seen in this star, when combined with the equally high $[\text{Fe}/\text{H}]$ derived in previous detailed abundance analysis of two other Galactic bulge dwarfs, both also highly magnified by microlensing, implies that the median metallicity in the Galactic bulge is very high. We thus infer that many previous estimates of the metallicity distribution in the Galactic bulge have substantially underestimated the mean Fe metallicity there due to sample bias, and suggest a candidate mechanism for such. If our conjecture proves valid, it may be necessary to update the calibrations for the algorithms used by many groups to interpret spectra and broadband photometry of the integrated light of very metal-rich old stellar populations, including luminous elliptical galaxies.

Subject headings: galaxies: bulges — Galaxy: bulge — gravitational lensing — stars: abundances

Online material: machine-readable table

1. INTRODUCTION

Microlensing occurs when a “lens” (star, planet, black hole, etc.) becomes closely aligned with a more distant “source” star, whose image it both magnifies and distorts. Normally the observer is most interested to learn about the lens, but microlensing data can simultaneously serve as a powerful probe of the source. If the source transits the lens (or the “caustics” generated by the lens, in the case of binary lenses), then it resolves the source, allowing detailed limb-darkening profiles from a photometric time series (Fields et al. 2003) or even spectral resolution of surface features like the chromosphere (Cassan et al. 2004) from judiciously taken spectra.

The lens can also serve simply to amplify the role of the telescope as a “light bucket.” Minniti et al. (1998) provocatively titled their report on observations of a bulge dwarf that was magnified by a factor $A = 2.25$ “Using Keck I as a 15 m Diameter Telescope” and Cavallo et al. (2003) presented a preliminary abundance analysis for six stars with small magnification ($2.5 < A < 30$), including this star and two other bulge dwarfs. Obviously, this trick could in principle be improved to arbitrary “diameters” simply by observing the events at higher magnification. The problem is that it is extremely difficult to recognize high-magnification events in advance, and harder still to activate large-telescope observations in time to take advantage of them. The process has been facilitated by microlensing planet hunters, who prize high-magnification events because of their extreme sensitivity to planets

(Udalski et al. 2005; Gould et al. 2006; Gaudi et al. 2008). Johnson et al. (2007) were the first to piggyback on the microlensing planet hunters, obtaining a 15 minute Keck spectrum of the Galactic bulge dwarf OGLE-2006-BLG-265S at magnification $A = 135$. This star, the first bulge dwarf with a high-quality spectrum, proved to be extremely metal-rich, a fact that might be telling us that the bulge is much more metal-rich than seems indicated by available spectra of giants, but could also just be the luck of the draw. The Johnson et al. (2007) results therefore substantially raised the premium on obtaining highly magnified spectra of bulge dwarfs.

On 2007 July 2, the OGLE collaboration⁵ (Udalski 2003) announced OGLE-2007-BLG-349 (R.A. = $18^{\text{h}}05^{\text{m}}24.43^{\text{s}}$; decl. = $-26^{\circ}25'19.0''$) at Galactic coordinates $(l, b) = (4.4, -2.5)$, i.e., 5.1° from the Galactic center, as a probable microlensing event. The Microlensing Follow Up Network⁶ (μFUN) began monitoring the event on August 18 to determine whether the event would be high-magnification and on September 3 issued a general alert that it would reach at least $A > 200$ two nights hence. On this basis, μFUN organized worldwide photometric observations, whose outcome will be reported elsewhere (S. Dong et al. 2008, in preparation), and also contacted J. G. C. at the Keck telescope to recommend intensive observations.

The ability to obtain high-resolution, high-quality spectra of Galactic bulge stars and to carry 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. Our abundance analysis of OGLE-2007-BLG-349S is described in the first few sections of the paper, with the key results presented in § 5. In an effort to explain our rather surprising results, we indicate in § 6 how past studies of the brightest giants, which are the only bulge stars for which detailed abundance analyses can be derived from spectra obtained under normal conditions,

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⁵ See <http://www.astrouw.edu.pl/~ogle/ogle3/ews/ews.html>.

⁶ See <http://www.astronomy.ohio-state.edu/~microfun>.

may be subject to previously ignored selection effects, and how this might impact studies of the integrated light for metal-rich old simple stellar populations. Abundance ratios in the Galactic bulge giants and in the microlensed dwarfs are discussed in § 7. A brief summary concludes the paper, while an Appendix discusses the behavior of selected diffuse interstellar bands in the spectrum of OGLE-2007-BLG-349S.

2. OBSERVATIONS

In light of the prediction that the magnification of the presumed Galactic bulge star OGLE-2007-BLG-349S would be very large, we decided to observe the object in an attempt to obtain a high signal-to-noise ratio and high-resolution spectrum. The night of 2007 September 5 was clear at the Keck Observatory, and the seeing⁷ was good, 0.8'' in the optical. We found the microlensed star, confirmed that it was bright, and took three consecutive spectra, each 1350 s in length. The UTCs at the end of each exposure were 06:03:14, 06:27:04, and 06:50:27. HIRES-R (Vogt et al. 1994) was used on the Keck I telescope in a configuration with coverage from 3900 to 8350 Å, with small gaps between the orders beyond 6650 Å. The slit was 0.86'' wide, giving a spectral resolution of 48,000.

The magnifications at the times of the three spectra were $A = 350$, $A = 390$, and $A = 450$; apparent I at these times ranged from 13.68 to 13.41 mag (S. Dong et al. 2008, in preparation). Hence our observations were carried out at a time when the amplification was larger by a factor of 3 than that of any previous highly magnified star with a high-resolution spectrum. While the signal-to-noise ratio (S/N) of the resulting summed spectrum is low for $\lambda < 5000$ Å (~ 30 per spectral resolution element at 4500 Å), not unexpected given the high extinction toward the Galactic bulge, the S/N per spectral resolution element in the continuum at $\lambda > 5500$ Å exceeds 90. Isolated lines with W_λ of 15 mÅ are easily detected at such wavelengths.

According to the microlensing model of S. Dong et al. (2008, in preparation) the source passed very close to a cusp shortly (roughly 2 hr) after the third observation. This means that the limb of the star was magnified more strongly than the center. We have calculated the maximum effect on the $V - I$ color due to differential magnification of the (cooler) limb of the star being more magnified than the center, with limb-darkening included, to be less than 0.005 mag during the spectroscopic exposures, and we ignore it.

3. STELLAR PARAMETERS

We determined T_{eff} for OGLE-2007-BLG-349S in three different ways, from line depth ratios of close pairs of temperature sensitive lines, from Fe I excitation, and from the ionization equilibrium between Fe I and Fe II.

Gray & Johanson (1991) have demonstrated that ratios of the central depth of selected pairs of lines that are close together in wavelength and highly sensitive to temperature can be used to deduce T_{eff} to high accuracy for cool stars. We checked the 15 such line pairs studied by Biazzo et al. (2007). In many cases one or both of the lines were highly saturated in the spectrum of OGLE-2007-BLG-349S, with central depths approaching 70% of the continuum. There were only three line pairs for which both lines had central depths of 40% or less. Using their polynomial fit for nonrotating dwarfs, we find a mean T_{eff} from these three pairs of 5350 K.

The Fe abundance was determined from 135 lines of Fe I and 11 of Fe II. As described in detail in § 4, $T_{\text{eff}} = 5400$ K produces a deduced Fe abundance independent of the excitation potential of the Fe I line and a difference between $[\text{Fe}/\text{H}]^8$ from Fe I versus from Fe II lines of only 0.08 dex, well within the expected uncertainty of $|\text{[Fe/H : Fe I]} - \text{[Fe/H : Fe II]}|$.

These three methods give a mean T_{eff} of 5431 K, with $\sigma = 72$ K. We adopt $T_{\text{eff}} = 5400 \pm 100$ K. The extinction-corrected $V - I$ color can be determined from the light curve of the microlensed star. The extinction to the source is taken to be that of the red clump stars on the horizontal branch in the neighborhood of the source, which is determined from OGLE II publicly available multicolor photometry. We assume that there is no differential extinction between the adjacent bulge red clump stars⁹ and the target. With this extinction, the model of S. Dong et al. (2008, in preparation) that fits the two-color (V and I , where the latter is in the Cousins system) microlensing light curve for OGLE-2007-BLG-349S fixes the flux level of the source to be $I_0 = 18.72$ mag with $(V - I)_0 = 0.73$ mag. Because the lens lies in the foreground disk (S. Dong et al. 2008, in preparation), the most probable distance to the source is that of the Galactic center, 8.0 kpc. The absolute magnitude is then $M_I = 4.22$. The bulge star is thus slightly fainter and slightly redder than the Sun ($V - I = 0.688 \pm 0.014$ mag; Holmberg et al. 2006). Combining this with the colors of stars along a metal-rich isochrone of Yi et al. (2001) suggests $T_{\text{eff}} = 5550$ K, 1.5 σ hotter than our adopted T_{eff} . If the extinction-corrected $V - I$ color determined in this way is underestimated by 0.08 mag (of which 0.05 mag may arise from an underestimate of the intrinsic color of the red clump), as was suspected by Johnson et al. (2007), who employed exactly the same method for OGLE-2006-BLG-265S, then the deduced T_{eff} for OGLE-2007-BLG-349S would be ~ 5430 K, essentially identical to that deduced from the spectrum itself.

We next turn to the surface gravity. With T_{eff} set, we can determine $\log(g)$ from the ionization equilibrium between Fe I and Fe II, from an isochrone, and from the line profile in the damping wings of a very strong line. The Galactic bulge is old (see, for example, Ortolani et al. 1995). We assume the age of OGLE-2007-BLG-349S is 9 Gyr. From the isochrones of Yi et al. (2001) we find the main-sequence turnoff occurs at 5500 K for $Z = 0.04$ (a metallicity 2.4 times solar) and no α -enhancement at an age of 9 Gyr. A star at 5400 K can be a subgiant with $\log(g) = 4.0$ dex, or a dwarf below the turnoff with $\log(g) = 4.4$ dex. For an upper main sequence star with a fixed T_{eff} , $\log(g)$ decreases by ~ 0.15 dex when the isochrone age is changed from 4 to 9 Gyr. Similarly, $\log(g)$ for a fixed age within this interval and metallicity ranging from $z = 0.00$ to $z = 0.06$ increases by ~ 0.10 dex. Thus our choice of an age of 9 Gyr for the isochrone we adopt to determine $\log(g)$ is not crucial, nor is the exact choice of metallicity of the isochrone.

Profiles of very strong lines with obvious damping wings can constrain $\log(g)$. Figure 1 shows a spectral synthesis in the region of the 6162.2 Å line of Ca I. A synthesis of the solar spectrum with the same line list gives a very good fit. The best fit for $\log(g)$ is 4.35 dex, supporting OGLE-2007-BLG-349S being a dwarf rather than a subgiant. Note that a solar $[\text{Ca}/\text{Fe}]$ ratio and $[\text{Fe}/\text{H}] = +0.5$ dex is assumed for this synthesis. In addition, the M_I of 4.22 mag deduced from the extinction combined with the microlensing light curve is 0.1 mag brighter than that of a 5400 K dwarf

⁸ We adopt the usual spectroscopic notations that $[A/B] \equiv \log(N_A/N_B)_* - \log(N_A/N_B)_\odot$, and that $\log \epsilon(A) \equiv \log(N_A/N_H) + 12.00$, for elements A and B.

⁹ The dereddened red clump in the Galactic bulge is assumed to have $I_0 = 14.32$ mag and $(V - I)_0 = 1.00$ mag.

⁷ The seeing was measured from the profile of the stellar image along the slit in the three individual spectroscopic exposures of OGLE-2007-BLG-349S.

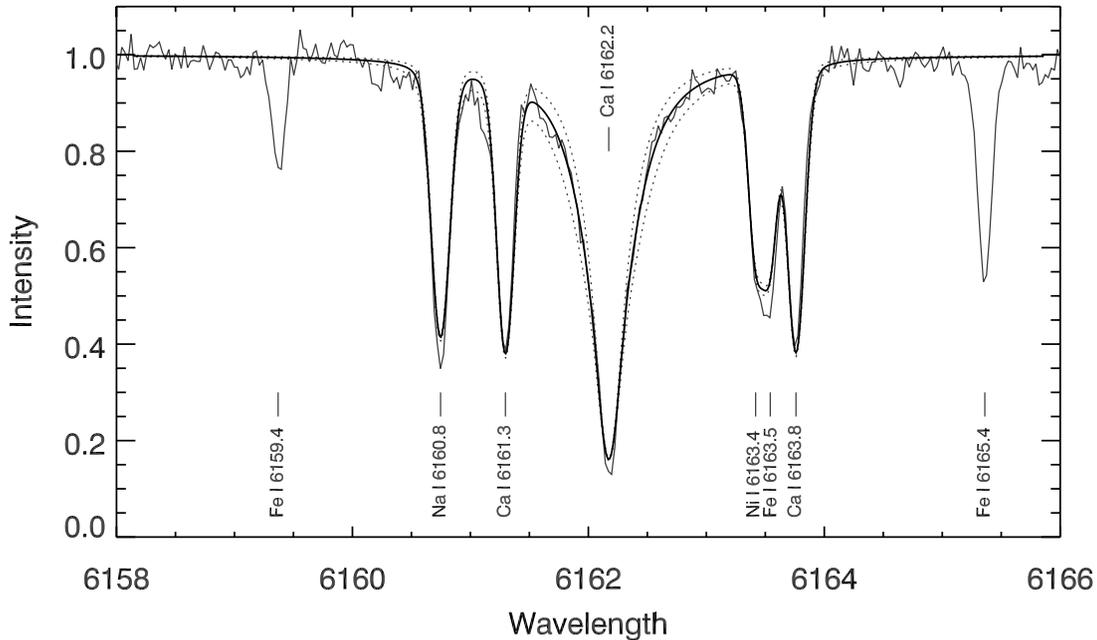


FIG. 1.— Spectrum of OGLE-2007-BLG-349S in the region of the strong Ca I line at 6162.2 Å is shown shifted to the rest frame. Overplotted as a thick line is a spectral synthesis covering 6160–6165 Å for $T_{\text{eff}} = 5400$ K, $[\text{Fe}/\text{H}] = +0.5$ dex, and solar $[\text{Ca}/\text{Fe}]$ with the best fit $\log(g)$ of 4.35 dex. The thin dashed lines represent offsets in $\log(g)$ of ± 0.3 dex.

with this isochrone, but is 1.0 mag fainter than that of a subgiant from that isochrone with that T_{eff} . The predicted number density for dwarfs as compared to subgiants is about 4:1 for a Salpeter initial mass function, further favoring the star being a dwarf. We thus feel confident that OGLE-2007-BLG-349S is a dwarf just below the main-sequence turnoff with $\log(g) \sim 4.4$ dex. The ionization equilibrium between Fe I and Fe II is satisfactory at $\log(g) = 4.5$ dex. The uncertainty in T_{eff} of 100 K translates into an uncertainty in $\log(g)$ of 0.2 dex. We adopt $\log(g) = 4.5 \pm 0.2$ dex for the abundance analysis.

4. ABUNDANCE ANALYSIS

Our Keck/HIRES spectrum of OGLE-2007-BLG-349S is full of strong lines with considerable blending and crowding, especially in the blue. Fe I lines at $\lambda < 5900$ Å were ignored, as were Fe II lines blueward of 5100 Å. For all other species, lines blueward of 5200 Å were excluded. A line list for Fe I and Fe II was assembled from that used by Fulbright et al. (2006) in their study of K giants in Baade’s window and from J. G. C.’s personal line list, augmented by selected very weak isolated lines found in the solar spectrum. Equivalent widths and atomic parameters for the lines used are given in Table 1. Lines with $W_\lambda > 180$ mÅ were rejected unless the species has very few detected features; those retained that are stronger than this are the only detected line of K I and the Na I $\lambda 5680$ doublet. (The NaD lines are much too strong to consider using and are hopelessly contaminated with interstellar absorption.) Equivalent widths were measured using an automatic Gaussian fitting routine combined with the measured heliocentric v_r of $+99.47 \pm 0.05$ km s $^{-1}$. The stronger lines were all checked by hand to make sure the damping wings were picked up when appropriate. The Mg I triplet lines in the region of 6320 Å, where there is a broad autoionization feature of Ca, were measured by hand. For elements with only a few detected lines, all features were checked by hand as well. The Fourier transform spectroscopy (FTS) solar spectrum of Wallace et al. (1998), available online, was very useful for this purpose. The major uncer-

tainty in the W_λ results from the definition of the continuum in the crowded spectrum of OGLE-2007-BLG-349S.

The abundance analysis follows the procedures laid out in Cohen et al. (2004). It was carried out differentially with respect to the Sun, since the T_{eff} difference is only ~ 400 K, and both stars are dwarfs. We used a current version of the LTE spectral synthesis program MOOG (Snedden 1973). We employ the grid of stellar atmospheres from Kurucz (1993) with $[\text{Fe}/\text{H}] = +0.5$ dex and solar abundance ratios without convective overshoot (Castelli & Kurucz 2003) and with the most recent opacity distribution functions. For consistency, the solar model was taken from the appropriate grid of Kurucz as well.

Spectral syntheses were used for the S I doublet near 6750 Å and for the Rb I resonance line near 7800 Å, which lies in the red wing of a much stronger Si I line. A synthesis of the CH band near 4320 Å using the molecular line list of Jorgensen et al. (1996) was carried out to determine the C abundances.

TABLE 1
 W_λ FOR OGLE-2007-BLG-349S

λ (Å)	Species	EP (eV)	$\log(gf)^a$ (dex)	W_λ (mÅ)
6707.76.....	Li I	0.00	0.178	≤ 5.0
7111.45.....	C I	8.64	-1.000	21.2
7115.32.....	C I	8.64	-0.600	27.0
7116.96.....	C I	8.64	-1.000	21.8
6300.30.....	[O I]	0.00	-9.720	≤ 8.6
7771.94.....	O I	9.15	0.369	52.2
7774.17.....	O I	9.15	0.223	54.6
7775.39.....	O I	9.15	0.001	40.8
5682.63.....	Na I	2.10	-0.700	194.1
5688.19.....	Na I	2.10	-0.420	214.1

NOTE.— Table is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.
^a An inverted solar analysis was used to determine gf .

Transition probabilities from the NIST Atomic Spectra Database Version 3.1 (Ralchenko et al. 2007) were used in general when available. Since we analyze OGLE-2007-BLG-349S differentially with respect to the Sun, the adopted gf values are not crucial, but when “accurate” values are available, we used them. Accurate gf values could not be located for a small number of lines for which we were forced to resort to an inverted solar analysis to assign such; these cases are indicated in Table 1. We used damping constants from Barklem et al. (2000) when available.

We set the microturbulent velocity v_t to 1.0 km s^{-1} , following the example of the Sun. This gave deduced Fe abundances independent of W_λ to within the accuracy that the resulting set of $\log[\epsilon(\text{Fe})]$ from each of Fe I lines could be measured. Hyperfine structure corrections were used for the lines of Ba II, Co I, Cu I, Mn I, Rb I, Sc II, and V I. These were taken from the compilation generated by Prochaska et al. (2000), except that the isotopic and hfs splittings for the Rb I $\lambda 7800$ line were taken from Lambert & Luck (1976).

Non-LTE corrections were not generally included, as this is a differential analysis with respect to the Sun, and the stellar parameters of OGLE-2007-BLG-349S are fairly close to those of the Sun. Two key elements for which this might be an issue are the O I $\lambda 7770$ triplet and our use of the resonance doublet of K I. We have checked the case of O using the fitting formula given in equation (2) of Bensby et al. (2004). When all the differences between the stellar parameters for the OGLE star and the Sun are taken into account, they yield a negligible difference in the non-LTE correction for this O triplet. Two sets of non-LTE calculations are available for the K I resonance doublet, of which we observed the redder line; the bluer line is in the middle of a strong terrestrial absorption band. The results of the two groups, given in Ivanova & Shimanskii (2000) and in Takeda et al. (2002), are consistent and suggest that for solar metallicity the K abundance of the OGLE star with respect to the Sun from a LTE analysis should be increased by about 0.08 dex to take into account the probable difference in the non-LTE correction for this line. This has been implemented here. However, this adopted value must be regarded as still uncertain since the non-LTE corrections for K are metallicity sensitive, and none are available for supersolar metallicity.

5. RESULTS OF THE ABUNDANCE ANALYSIS

The final deduced abundances for OGLE-2007-BLG-349S for 28 species of 26 elements are given in Table 2. Our derived absolute abundances, the abundances relative to the Sun, and the abundance ratios $[X/\text{Fe}]$ are given in this table. 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 σ_{obs} . This is calculated from the set of differences between the deduced solar abundance for the species in question and that found for OGLE-2007-BLG-349S for each observed line of the species. Thus neither random nor systematic errors in the gf values contribute to σ_{obs} .

While the absolute abundance for a given species listed in Table 2 will be affected by any systematic error in the gf values of the lines we use here, relative abundances $[X/\text{Fe}]$ will not, since we have carried out a differential analysis with respect to the Sun. An uncertainty for $[X/\text{Fe}]$ for each species, σ_{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 $[\text{Fe}/\text{H}]$ of OGLE-2007-BLG-349S versus the value +0.5 dex of the model atmospheres we are using. The fifth term, the contribution for errors in W_λ , is set to 0.05 dex if only one or

two lines were measured; for a larger number of detected lines we adopt $\sigma_{\text{obs}}/[N(\text{lines})]^{1/2}$ for this term. This is added in quadrature to the other four terms. Uncertainties in the absolute abundances have only been calculated for Fe as inferred from Fe I and from Fe II lines and are given below.

The sensitivity of the deduced abundances to changes in the stellar parameters or in v_t is shown in Table 3 for absolute abundances and in Table 4 for relative abundances $[X/\text{Fe}]$. As expected, the latter show much weaker dependences on the choice of stellar parameters, etc. These entries were used to generate the values of σ_{pred} in the last column of Table 2. Table 3 shows that the Fe I abundance $\log[\epsilon(\text{Fe})]$ is almost independent of the choice of T_{eff} , increasing by only +0.12 dex when T_{eff} is increased by 250 K. The neutral species of elements with resonance or low-excitation lines (K I, V I, Rb I, and Zr I) show the largest increase in deduced abundance when T_{eff} is increased, while those species with only high excitation lines (the near-IR O triplet, C I, and S I) show the opposite dependence on T_{eff} , as expected. The ionization equilibrium for Fe for the adopted T_{eff} and $\log(g)$ is good, as is the Fe I excitation equilibrium.

In addition to presenting what we believe to be the first abundance determinations for Rb and for Zr for any star in the Galactic bulge, there are three key results of the detailed abundance analysis we have carried out of OGLE-2007-BLG-349S. The first is the very high metallicity we derive. We find that $[\text{Fe}/\text{H}]$ is $+0.51 \pm 0.09$ dex from 135 Fe I lines and $+0.43 \pm 0.17$ dex from 11 Fe II lines. To achieve a reduction of $[\text{Fe}/\text{H}]$ to $<+0.3$ dex, T_{eff} must be reduced to ~ 5000 K, with a change of $\log(g)$ of +0.2 dex for the dwarf or -0.1 dex for the subgiant, for the star to lie on the appropriate isochrone. The Fe ionization equilibrium will then be altered by 0.3 dex for the dwarf case and by somewhat less for the subgiant. This will produce a Fe ionization equilibrium that is so far from equality that the altered set of stellar parameters must be rejected. To achieve solar metallicity and reasonable Fe ionization equilibrium is simply not possible with any set of stellar parameters that lie on the relevant isochrone.

Second, the α -elements O and Mg do not show any excess with respect to Fe; oxygen, which is the most abundant α -element, has subsolar $[\text{O}/\text{Fe}]$. Finally, in all species for which the abundance is regarded as well determined (the notes in the last column of Table 2 indicate the major concerns), there are no credible deviations from the solar ratios.

We note that $[\text{Fe}/\text{H}]$ cannot be affected by mixing of nuclear processed material from the interior of a dwarf or a red giant, as none would have been produced up to that stage of stellar evolution. Furthermore, any diffusion of Fe into the more quiescent dwarf as compared to the stirred-up outer layers of the giant would be small in such high-metallicity stars and would only make the present conundrum of the unexpectedly high $[\text{Fe}/\text{H}]$ we find in OGLE-2007-BLG-349S worse. We also note that the three line ratios we used as one method for determining T_{eff} detailed in § 3 each consisted of a V I line paired with either a Fe I, Ni I, or Si I line. We find $[\text{V}/\text{Fe}]$ for OGLE-2007-BLG-349S to be $+0.17 \pm 0.14$ dex (Table 2). If this ratio is actually slightly above solar, a slight underestimate of T_{eff} would result from the line ratio method. Underestimating T_{eff} is equivalent to underestimating $[\text{Fe}/\text{H}]$, which again makes the discrepancy with the bulge giants worse.

6. OGLE-2007-BLG-349S AND THE METALLICITY DISTRIBUTION OF THE GALACTIC BULGE

An early attempt to determine the metallicity distribution in the Galactic bulge was that of Sadler et al. (1996), who used low-resolution spectroscopy for 268 bulge giants and red clump stars to derive a mean $[\text{Fe}/\text{H}]$ of -0.11 ± 0.04 dex. Ramírez et al.

TABLE 2
ABUNDANCES IN OGLE-2007-BLG-349S

Species	$\log[\epsilon(X)]^a$ (dex)	σ_{obs}^b (dex)	Number of Lines	$\log[\epsilon(X)/\epsilon(X)_\odot]$ (dex)	$[X/\text{Fe}]^c$ (dex)	σ_{pred} for $[X/\text{Fe}]$ (dex)	Notes
Li I.....	≤ 0.86	...	1	$\leq +0.06$	≤ -0.45	0.13	Syn.
C I.....	8.92	0.07	3	+0.31	-0.12	0.21	High χ .
C(CH).....	9.05	0.15	Band	+0.39	-0.12	0.17	Syn.
O I.....	9.07	0.12	3	+0.14	-0.29	0.19	High χ .
Na I.....	6.64	0.11	4	+0.77	+0.26	0.09	...
Mg I.....	8.16	0.10	4	+0.59	+0.08	0.07	...
Al I.....	6.82	0.04	2	+0.49	+0.13	0.08	...
Si I.....	8.00	0.12	6	+0.47	+0.04	0.17	High χ .
Si I.....	7.62	...	1 ^d	+0.45	+0.02	0.20	Syn, high χ .
K I.....	5.61	...	1	+0.38	-0.13	0.12	A 0.08 dex non-LTE correction relative to the Sun is included for K I.
Ca I.....	6.58	0.14	11	+0.55	+0.04	0.07	...
Sc II.....	3.71	0.03	2	+0.54	+0.13	0.10	The HFS corrections are small and not an issue.
Ti I.....	5.36	0.12	8	+0.53	+0.02	0.11	...
Ti II.....	5.57	...	1	+0.67	+0.24	0.10	...
V I.....	4.47	0.06	5	+0.68	+0.17	0.14	The HFS corrections are small and not an issue.
Cr I.....	6.19	0.11	7	+0.53	+0.02	0.07	...
Mn I.....	6.03	0.11	3	+0.66	+0.15	0.11	The HFS corrections are large and are a concern.
Fe I.....	7.97	0.15	135	+0.51	0.00	0.09 ^e	...
Fe II.....	7.92	0.10	11	+0.43	-0.08	0.17 ^f	...
Co I.....	5.55	0.14	5	+0.77	+0.26	0.08	The HFS corrections are small and not an issue.
Ni I.....	6.86	0.13	22	+0.67	+0.16	0.05	...
Cu I.....	4.74	...	1	+0.79	+0.28	0.15	The HFS corrections are very large and are a major concern.
Zn I.....	4.97	...	1	+0.42	-0.09	0.13	...
Rb I.....	3.35	0.15	1	+0.65	+0.13	0.17	Syn.
Zr I.....	3.28	0.01	3	+0.39	-0.14	0.16	...
Ba II.....	2.50	0.05	3	+0.38	-0.05	0.17	The HFS corrections are small and not an issue.
La II.....	1.98	0.01	2	+0.97	+0.54	0.12	Only one or two very weak lines detected. Could be upper limits.
Eu II.....	1.38	...	1	+0.88	+0.45	0.10	Only one or two very weak lines detected. Could be upper limits.

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

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

^c The reference species (Fe I or Fe II) is given in Table 4.

^d Very close pair of lines on wing of much stronger Si I line.

^e The uncertainty in $[\text{Fe}/\text{H}]$ inferred from the 135 Fe I lines.

^f The uncertainty in $[\text{Fe}/\text{H}]$ inferred from the 11 Fe II lines.

TABLE 3
SENSITIVITY OF DEDUCED ABSOLUTE ABUNDANCES

Species	$\Delta \log[\epsilon(x)]$ for $\Delta T_{\text{eff}} + 250$ K (dex)	$\Delta \log[\epsilon(x)]$ for $\Delta \log(g) + 0.5$ dex (dex)	$\Delta \log[\epsilon(x)]$ for $\Delta v_t = + 0.2$ km s ⁻¹ (dex)	$\Delta \log[\epsilon(x)]$ for $\Delta [\text{Fe}/\text{H}]$ model + 0.5 dex (dex)
Li I.....	0.27	-0.02	0.00	0.01
O I ^a	-0.01	0.25	0.00	0.22
O I ^b	-0.32	0.17	-0.01	0.03
C I.....	-0.29	0.17	-0.01	0.00
CH.....	0.20	-0.11	-0.05	0.04
Na I.....	0.18	-0.19	-0.02	0.12
Mg I.....	0.08	-0.09	-0.03	0.06
Al I.....	0.14	-0.06	-0.03	0.04
Si I.....	-0.07	-0.01	-0.02	0.10
S I.....	-0.21	0.16	-0.01	0.01
K I.....	0.25	-0.24	-0.03	0.15
Ca I.....	0.20	-0.11	-0.05	0.07
Sc II.....	-0.02	0.22	-0.04	0.18
Ti I.....	0.25	-0.01	-0.02	0.02
Ti II.....	-0.05	0.22	-0.02	0.17
V I.....	0.33	-0.03	-0.07	-0.01
Cr I.....	0.18	-0.08	-0.04	0.06
Mn I.....	0.20	-0.18	-0.07	0.16
Fe I.....	0.12	-0.04	-0.05	0.10
Fe II.....	-0.19	0.24	-0.05	0.19
Ni I.....	0.06	0.00	-0.05	0.13
Co I.....	0.12	0.05	-0.05	0.07
Cu I.....	0.17	-0.11	-0.07	0.24
Zn I.....	-0.13	0.13	-0.03	0.12
Rb I.....	0.22	-0.03	-0.03	0.00
Zr I.....	0.35	-0.02	-0.01	0.00
Ba II.....	0.06	0.09	-0.11	0.26
La II.....	0.04	0.22	-0.01	0.20
Eu II.....	-0.02	0.22	-0.02	0.18

^a For 6300 Å line of [O I], only an upper limit here.

^b For the three lines of the O I $\lambda 7770$ triplet.

(2000) studied a sample of M giants in the near-IR; they found a very similar mean $[\text{Fe}/\text{H}]$ of -0.21 dex with a dispersion of 0.30 dex. Zoccali et al. (2003) used extensive optical and near-IR photometry with color-magnitude diagram (CMD) fitting; they derived a somewhat lower mean $[\text{Fe}/\text{H}]$. In all these cases, the calibration of the metallicity scale relied on Galactic globular clusters (GCs). Zoccali et al. (2003) suggest that the differences between several of these studies depend crucially on the abundances adopted for the two highest metallicity GCs with high-resolution abundance analyses, NGC 6553 and NGC 6558. $[\text{Fe}/\text{H}]$ values for these two GCs have ranged over more than 0.5 dex in the literature, but since the work of Cohen et al. (1999) and Carretta et al. (2001), who suggested values higher than most previous studies, more recent analyses have settled toward the higher values (see, e.g., Zoccali et al. 2004; Alves-Brito et al. 2006).

An early high dispersion spectroscopic study of Galactic bulge K giants is that of McWilliam & Rich (1994), who found a mean $[\text{Fe}/\text{H}]$ in their sample of -0.25 dex. Fulbright et al. (2006) updates and expands on this earlier work. They then use their detailed abundance analyses of 27 K giants in Baade's window to recalibrate the metallicities for the much larger samples of Sadler et al. (1996) and of Rich (1988). The mean $[\text{Fe}/\text{H}]$ they thus deduce is -0.10 ± 0.04 dex. The median $[\text{Fe}/\text{H}]$ of their sample is also subsolar. As infrared echelle spectrographs have become available on 8 m class telescopes, high-dispersion studies of Galactic bulge giants in the near-IR have become possible (see, e.g., Rich & Origlia 2005; Cunha & Smith 2006; Rich et al. 2007). The

mean $[\text{Fe}/\text{H}]$ from the sample of M giants studied by Rich et al. (2007) in the Galactic bulge is well below solar, with $[\text{Fe}/\text{H}] = -0.22 \pm 0.01$ dex. The median Fe metallicity of the small sample of giants with near-IR spectra analyzed by Cunha & Smith (2006) is also slightly below solar metallicity. Since this sample largely overlaps that of Fulbright et al. (2006), it is not included in the figures.

Very recently, Zoccali et al. (2008) have presented initial results of a survey of Fe metallicity in the Galactic bulge from spectra with $\lambda/\Delta\lambda = 20,000$ of about 800 stars. They find a radial gradient in $[\text{Fe}/\text{H}]$ within the bulge with the mean value going from $+0.03$ dex at $b = -4^\circ$ to -0.12 dex at $b = -6^\circ$, and a sharp cut-off toward higher metallicities.

All of these samples of Galactic bulge stars are of luminous giants and/or of red clump stars. They all have mean and median $[\text{Fe}/\text{H}]$ values that are slightly subsolar and are similar to the mean $[\text{Fe}/\text{H}]$ of -0.1 dex found for local disk stars by Allende Prieto et al. (2004). Yet OGLE-2007-BLG-349S, analyzed here, and OGLE-2006-BLG-265S (Johnson et al. 2007), another Galactic bulge microlensed dwarf with a high-quality detailed abundance analysis, both have $[\text{Fe}/\text{H}] \sim +0.5$ dex; the third such star found to date, MOA-2006-BLG-099S, with a lower signal-to-noise ratio spectrum analyzed by Johnson et al. (2008) has a somewhat lower Fe metallicity, $[\text{Fe}/\text{H}] = +0.36 \pm 0.18$ dex. The comparison between the $[\text{Fe}/\text{H}]$ distribution for the recalibrated sample of Sadler et al. (1996) by Fulbright et al. (2006) and the $[\text{Fe}/\text{H}]$ values deduced for these three Galactic-bulge dwarfs is shown in Figure 2. While three stars is an uncomfortably small sample, it is

TABLE 4
SENSITIVITY OF DEDUCED RELATIVE ABUNDANCES

Species	$\Delta[X/Fe]$ for $\Delta T_{\text{eff}} + 250$ K (dex)	$\Delta[X/Fe]$ for $\Delta \log(g) + 0.5$ dex (dex)	$\Delta[X/Fe]$ for $\Delta v_r = +0.2$ km s ⁻¹ (dex)	$\Delta[X/Fe]$ for $\Delta [Fe/H]$ model + 0.5 dex (dex)	Reference ^a
Li I.....	0.15	0.02	0.05	-0.09	1
O I ^b	-0.13	0.29	0.05	0.12	1
O I ^c	-0.13	-0.07	0.04	-0.16	2
C I.....	-0.10	-0.07	0.04	-0.19	2
CH.....	0.08	-0.07	0.00	-0.06	1
Na I.....	0.06	-0.15	0.03	0.02	1
Mg I.....	-0.04	-0.05	0.02	-0.04	1
Al I.....	0.02	-0.02	0.02	-0.06	1
Si I.....	0.12	-0.25	0.03	-0.09	2
S I.....	-0.02	-0.08	0.04	-0.18	2
K I.....	0.13	-0.20	0.02	0.05	1
Ca I.....	0.08	-0.07	0.00	-0.03	1
Sc II.....	0.17	-0.02	0.01	-0.01	2
Ti I.....	0.13	0.03	0.03	-0.08	1
Ti II.....	0.14	-0.02	0.03	-0.02	2
V I.....	0.21	0.01	-0.02	-0.11	1
Cr I.....	0.06	-0.04	0.01	-0.04	1
Mn I.....	0.08	-0.14	-0.02	0.06	1
Co I.....	0.00	0.09	0.00	-0.03	1
Ni I.....	-0.06	0.04	0.00	0.03	1
Cu I.....	0.05	-0.07	-0.02	0.14	1
Zn I.....	-0.25	0.17	0.02	0.02	1
Rb I.....	0.10	0.01	0.02	-0.10	1
Ba II.....	0.25	-0.15	-0.06	0.07	2
Zr I.....	0.23	0.02	0.04	-0.10	1
La II.....	0.23	-0.02	0.04	0.01	2
Eu II.....	0.17	-0.02	0.03	-0.01	2

^a 1 denotes a value of $[X/Fe]$ where Fe I is used as the reference, while for 2, Fe II is used.

^b For 6300 Å line of [O I], only an upper limit here.

^c For the three lines of the O I $\lambda 7770$ triplet.

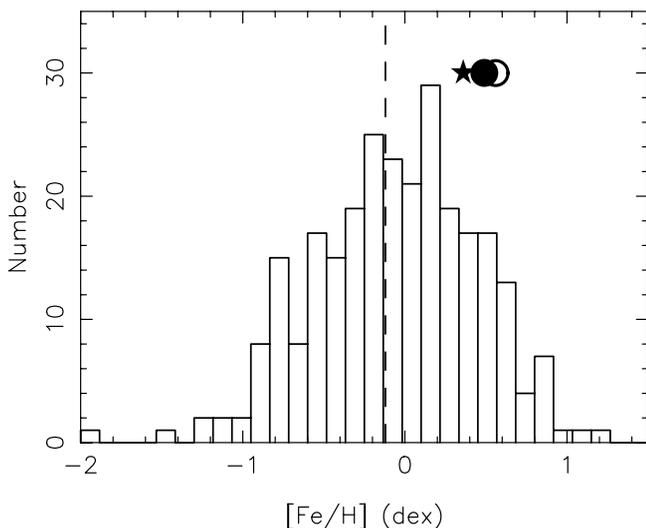


FIG. 2.— Fe metallicity distribution for the sample of 268 Galactic bulge stars from Sadler et al. (1996) as recalibrated by Fulbright et al. (2006). The median at $[Fe/H] = -0.12$ dex is indicated by the dashed vertical line. The $[Fe/H]$ values for the three microlensed bulge dwarfs, OGLE-2007-BLG-349S studied here (*large filled circle*), OGLE-2006-BLG-265S (Johnson et al. 2007; *large open circle*), and MOA-2006-BLG-099S (Johnson et al. 2008; *star*), are marked.

difficult to believe that this is consistent with the published metallicity distributions for the Galactic-bulge giants and/or red clump stars. The probability that the sample of three stars would have such high $[Fe/H]$ values by chance is less than 1% given the $[Fe/H]$ distributions of the larger of the relevant studies in the Galactic bulge claiming to have unbiased samples, including Ramírez et al. (2000) with 110 M giants, which must be considered unbiased at the high-metallicity end, Sadler et al. (1996; 268 bulge stars), and the recalibrated version of the latter by Fulbright et al. (2006). A Kolmogorov-Smirnov test shows that the probability of finding the three carefully studied microlensed bulge dwarfs at their very high $[Fe/H]$ values if the underlying metallicity distribution is that found by Zoccali et al. (2008) from high-dispersion spectra of a very large sample of giants in three bulge fields is less than 10^{-4} . This calculation takes into account the radial gradient in the metallicity distribution function found by Zoccali et al. (2008).

We next assemble the evidence that OGLE-2007-BLG-349S is actually a dwarf in the Galactic bulge. We have already demonstrated that the microlensed bulge dwarf studied here has stellar parameters that, when combined with the unlensed magnitude from the microlensing light curve, yield an unlensed luminosity consistent with that expected for a dwarf of its T_{eff} at the distance of the Galactic center. This is true to within 0.2 mag for the other two such stars as well, OGLE-2006-BLG-265S and MOA-2006-BLG-099S (Johnson et al. 2007, 2008). The three microlensed bulge dwarfs studied to date come from a kinematically hot population; they have radial velocities of +99, -154, and +113 km s⁻¹ with a typical uncertainty of less than 2 km s⁻¹, thus showing a

dispersion in v_r , consistent with that inferred from large samples of bulge giants (see, e.g., Sadler et al. 1996; Zoccali et al. 2008).

About 4% of the dwarfs in the solar neighborhood from the proper-motion sample of Grenon (1989) appear to be old and very metal-rich, with $[M/H] > +0.30$ dex. These stars are almost all on eccentric orbits with small pericenters ($\lesssim 3$ kpc). Castro et al. (1997) and Pompéia et al. (2003) have carried out detailed abundance analyses of some of these stars to find that the most metal-rich of them reach $[Fe/H] +0.55$ dex, and have solar abundance ratios in general. These local dwarfs are thus similar in their abundances to OGLE-2007-BLG-349S. The references cited suggest that they are possibly stars on chaotic orbits ejected from the Galactic bar or older central regions of the Galactic disk. Little is known about the inner regions of the Galactic disk, whether it exists at all in the inner kpc, or what its scale height might be should it exist. The model of Binney et al. (1997) constructed to reproduce the surface brightness within 5 kpc of the Galactic center seen by *COBE* DIRBE at 3.5 and at 4.9 μm after correction for extinction, suggests a double exponential disk with a scale heights of 42 and of 210 pc (1.5° at a distance of 8 kpc to the Galactic center) combined with a truncated power-law bulge. However, the beam size of *COBE* DIRBE is $0.7^\circ \times 0.7^\circ$, and this was smoothed to a 1.5° angular resolution for their analysis. The scale height of 210 pc thus corresponds to their minimum angular resolution, and may well be smaller, which would reduce any potential disk contamination of bulge samples. In any case, using their model as a guide, we find that the probability of contamination by disk stars of a sample at $b = 2.5^\circ$ in this maximal case is only $\sim 30\%$ larger than it is at $b = 4^\circ$. Some disk models such as model 2 of Lopez-Corrodoira et al. (2005), constructed to fit 2MASS star counts, contain an inner hole, which would lower potential disk contamination of bulge samples substantially.

Rather than speculate further on whether or not there is a disk within the central kpc and what its properties might be, we refer back to the large samples of “bulge” giants studied in the many references cited above. The innermost field included in most of these is Baade’s window, with b ranging from -3.9° to -4.1° . The galactic latitudes for the three microlensed dwarfs are -2.5° , -3.6° , and -4.8° , so that two of these are slightly smaller than that of Baade’s window. However, recently Rich et al. (2007) presented a detailed abundance analysis from near-IR spectra of M giants in a field at $(l, b) = (0^\circ, -1^\circ)$, significantly closer to the Galactic center than any of the three microlensed dwarfs. Their sample of 17 M giants has the usual properties seen in the Baade’s window samples, a mean $[Fe/H]$ of -0.22 dex, with the most metal rich at $[Fe/H] +0.02 \pm 0.11$ dex. These giants show the usual α -enhancement. Surely the microlensed dwarfs, each located more than twice as high above the Galactic plane than the giants in this inner bulge field, cannot then be from a different population than the Rich et al. (2007) M giant sample; we thus do not believe that the sample of microlensed bulge stars is contaminated by any disk stars that might be collocated near the Galactic center.

We suggest that sample bias is responsible for the difference between the median Fe metallicity seen in the bulge giant samples and that of the microlensed bulge dwarfs. A possible mechanism is the very high mass loss rates predicted to occur at the very high metallicities and moderately high luminosities being discussed here. These are high enough that in an old stellar population, stars are predicted to lose enough mass to peel off the red giant branch (RGB) before reaching the He flash, which they never go through. Red clump stars, which are burning He in their cores on the horizontal branch, are even more evolved than giants at the RGB tip, and so their evolutionary tracks, once mass loss is

properly taken into account, may indicate that their expected numbers in an old very metal-rich population may be even more depleted than are luminous first ascent RGB stars. This effect may have been detected through CMD studies of the extremely metal-rich open cluster NGC 6791 with $[Fe/H] +0.45$ dex (Carretta et al. 2007). In this cluster, Kalirai et al. (2007) found a strong relative absence of luminous RGB stars. We propose that this relative paucity of giants on the upper RGB for very metal-rich old populations produces a bias against the highest metallicity stars by preferentially eliminating them from the samples being studied by all previous investigations in the Galactic bulge, which samples consist of one or more of the luminous K giants, luminous M giants, and red clump stars found there.

If this is correct, then the mean bulge metallicity may be comparable to that expected from the radial gradients prevailing within the Galactic disk at a time ~ 5 Gyr ago extrapolated to the Galactic center. It thus may be that at the present time there is a gradient within the solar circle of stellar metallicity with Galactic radius that is roughly comparable to that measured for the interstellar medium (ISM) at present from H II regions by Esteban et al. (2005) and from planetary nebulae (PNe) by Maciel et al. (2007). The latter present an estimate of the change of the radial abundance gradient in the Galaxy as a function of time from PNe of varying ages. They suggest that the radial abundance gradient in the ISM in the Galactic disk was twice as large ~ 5 Gyr ago when the Sun was formed than it is now.

There are important consequences for the chemical evolution of extragalactic objects as well if our conjecture regarding the metallicity distribution of the Galactic bulge is correct. The interpretation of spectra and broadband photometry of the integrated light of simple old metal-rich stellar populations such as are believed to exist in luminous elliptical galaxies may be affected. We expect an underestimate of the true Fe metallicity of such systems to occur with commonly used tools such as Lick indices, calculated with stellar evolutionary tracks and isochrones that ignore mass loss, as is normally the case. We expect an overestimate of the mass-to-light ratio to occur if the luminous RGB stars we expect to be present near the RGB tip in a metal-rich population are not present in their expected numbers, as they contribute only a small fraction of the mass, but a larger fraction of the total luminosity. Changes in the strength of specific absorption features can be expected as well, particularly in the IR, where luminous red giants dominate the integrated light assuming they are present.

7. ABUNDANCE RATIOS

Many previous analyses of Galactic bulge K and M giants have found enhanced α/Fe ratios when compared to both the thick and thin disk stars for which very accurate abundance ratios for many elements for large samples exist (see, e.g., Reddy et al. 2003; Bensby et al. 2005). Abundance ratios help illuminate the star formation history of the bulge, and the contributions to its chemical inventory as a function of time of SN Ia, SN II, and AGB stars. The α -enhancement found in Galactic bulge giants has been viewed as an indication that chemical evolution proceeded more rapidly in the Galactic bulge than in either the Galactic thick or thin disk population. In particular, Matteucci & Brocato (1990) discuss the role of O and Mg as probes of the contribution of massive stars; see Ballero et al. (2007) for a current model. McWilliam et al. (2008) revisit this issue, suggesting that metallicity-dependent mass loss rates or nucleosynthesis yields may be important in this context. Such findings help to determine the mode of formation of the Galactic bulge, whether it is a classical bulge or one formed over a longer timescale through secular evolution of the disk. Detailed discussion of these options and references to the

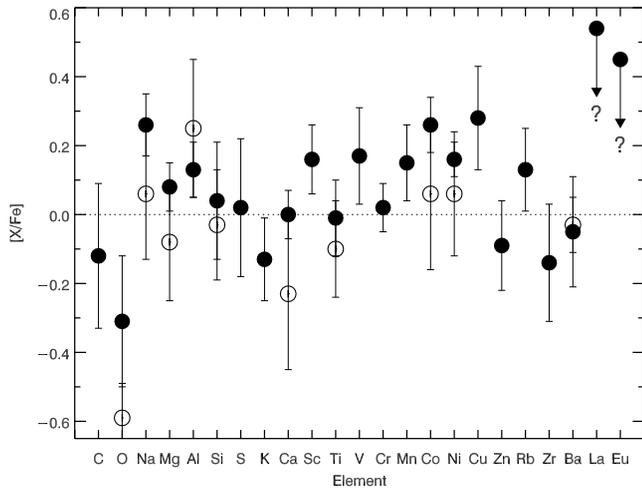


FIG. 3.— Abundance ratios for various species are shown for OGLE-2007-BLG-349S analyzed here (*filled circles*) and for OGLE-2006-BLG-265S (*open circles*) from Johnson et al. (2007).

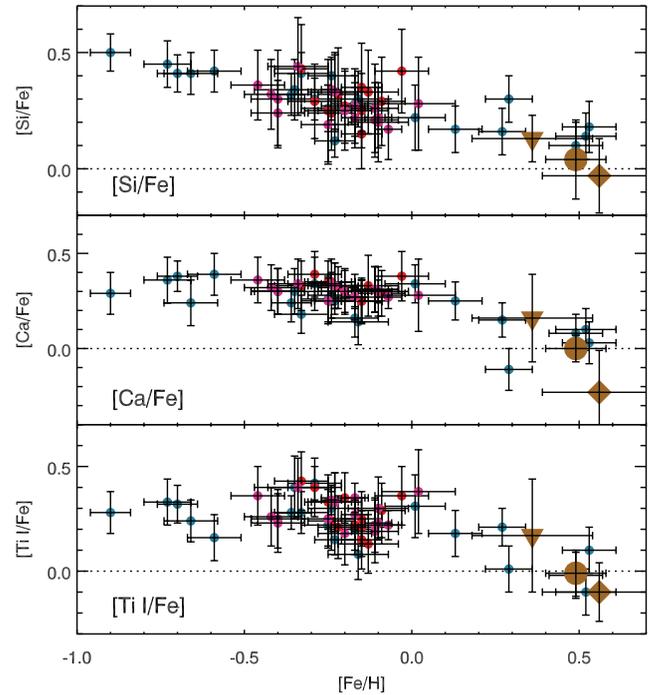


FIG. 5.— The same as Fig. 4 for [Si/Fe], [Ca/Fe], and [Ti I/Fe]. The symbols are the same as in Fig. 4.

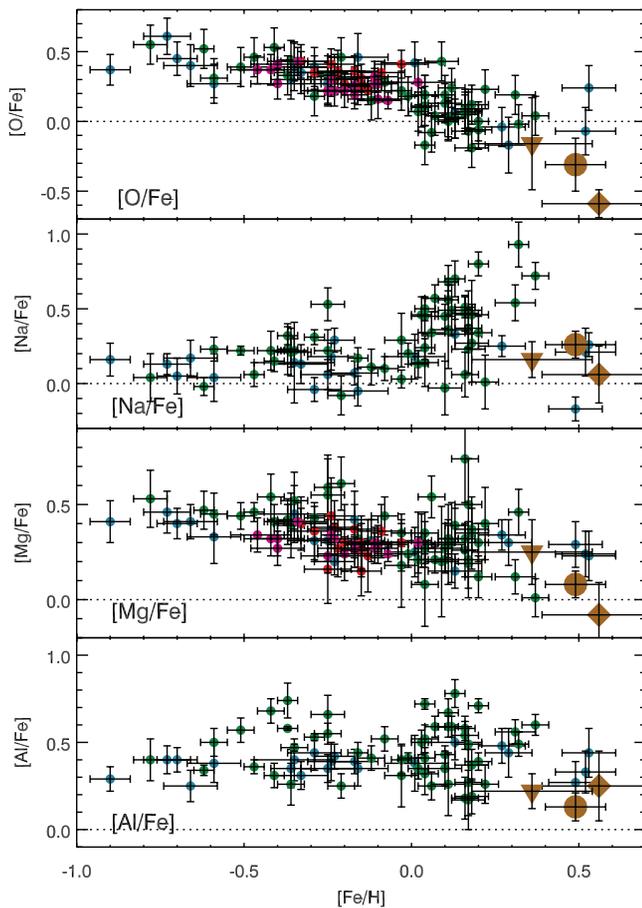


FIG. 4.— Abundance ratios [O/Fe], [Na/Fe], [Mg/Fe], and [Al/Fe] are shown as a function of [Fe/H]. The three microlensed stars are indicated by large brown symbols: OGLE-2007-BLG-349S (*filled circle*), OGLE-2006-BLG-265S from Johnson et al. (2007; *diamond*), and MOA-2006-BLG-099S from Johnson et al. (2008; *triangle*). They are shown superposed on those for samples of bulge M and K giants of Fulbright et al. (2007; *blue circles*), Rich & Origlia (2005; *red circles*), Lecureur et al. (2007; *green circles*), and for M giants in the inner bulge from Rich et al. (2007; *pink circles*).

relevant theoretical studies can be found in, for example, Lecureur et al. (2007).

Rapidly increasing samples of luminous stars in the bulge, both in terms of numbers of stars analyzed and in terms of the accuracy of the results, are now becoming available. Fulbright et al. (2007) gives a detailed discussion of α -enhancement in their sample of Galactic bulge K giants. They find enhanced [O/Fe], [Mg/Fe], and [Al/Fe] compared both to the solar ratios and to those in both thick and thin disk stars, even in supersolar bulge K giants, and discuss the different behavior of the hydrostatic (including O and Mg) and explosive (including Si, Ca, and Ti) α -elements; only the former appear enhanced in the bulge giants. Recently, initial results from a major high dispersion spectroscopic survey of Galactic bulge giants and red clump stars being carried out at the Very Large Telescope have been reported by Zoccali et al. (2006), with more details in Lecureur et al. (2007). They present the analysis of a sample of 53 stars selected to span the color range of bulge giants.

However, our analysis of OGLE-2007-BLG-349S (see Table 2) finds [Mg/Fe] has the solar ratio and [O/Fe] is subsolar. Johnson et al. (2007) find similar low ratios in OGLE-2006-BLG-265S. The third microlensed star, MOA-2006-BLG-099S, shows a small α -enhancement, but the uncertainties are large, and a 1σ deviation toward smaller values would make them consistent with the solar values. Subsolar [O/Fe] is found in all three microlensed dwarfs. Figure 3 shows the abundance ratios [X/Fe] for each species detected in one of both of the two bulge dwarfs with [Fe/H] $\sim +0.5$ dex. Figures 4 and 5 display the abundance ratios for the three microlensed Galactic bulge dwarfs for several elements as a function of [Fe/H] as compared to recent results from samples of luminous Galactic bulge giants.

A comparison of [Mg/Fe] with [Al/Fe] for the two microlensed bulge dwarfs compared to the results from the samples of bulge giants of Lecureur et al. (2007) and of Fulbright et al. (2007) is shown in Figure 6. The three microlensed bulge dwarfs lie at the low end of the distribution in [Mg/Fe] and at the extreme low end of that for [Al/Fe]. Also intriguing is that Lecureur et al.

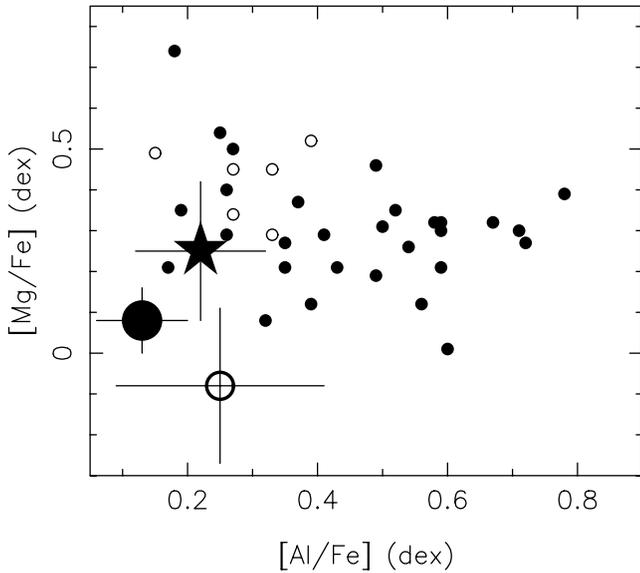


FIG. 6.—The $[Mg/Fe]$ ratio vs. the $[Al/Fe]$ ratio for OGLE-2007-BLG-349S, analyzed here, is shown as the large filled circle, OGLE-2006-BLG-265S from Johnson et al. (2007) as the large open circle, and MOA-2006-BLG-099S from Johnson et al. (2008) as the large star. Those stars with $[Fe/H] > 0.0$ dex from the samples of bulge giants and red clump stars of Lecureur et al. (2007) are shown as small filled circles, and those from the sample of Fulbright et al. (2007) as small open circles. Error bars (1σ) are shown for the three OGLE dwarfs; those of the two samples of bulge giants are similar to those for OGLE-2006-BLG-265S taken from Johnson et al. (2007).

(2007) finds evidence for variations among the giants of highest metallicity in their sample of $[O/Fe]$, $[Na/Fe]$, $[Mg/Fe]$, and $[Al/Fe]$ that substantially exceed their claimed uncertainties. This is accompanied by an anticorrelation between $[O/Fe]$ and $[Na/Fe]$ and by a correlation of $[Na/Fe]$ with $[Al/Fe]$, which is very reminiscent of the star-to-star abundance variations found within Galactic globular clusters, as summarized in the recent review of Gratton et al. (2004).

As is shown in Figures 4 and 5, the microlensed dwarfs show no sign of α -enhancement, while the bulge giants have $[Mg/Fe]$ (as well as $[Na/Fe]$ and $[Al/Fe]$) enhanced even at supersolar metallicities. What is causing this difference? Why do the giants show a such large range in $[X/Fe]$ for several key light elements? Are the giants mixed? Are there substantial non-LTE corrections which are not being included correctly?

The key question is which of the two, bulge giants or microlensed bulge dwarfs, best represents in its atmosphere today the initial chemical inventory of the star, i.e., of the ISM at the time the star was formed. It must be noted that the study of microlensed Galactic dwarfs can be carried out differentially with respect to the Sun, as we did here, while those of cool giants are forced to rely on Arcturus and/or μ Leo as the reference. This difference may give rise to potentially substantial systematic errors in the analysis which may depend on T_{eff} of the star. A probable example of such a systematic error can be seen in the $[Si/Fe]$ panel of Figure 3 of Preston et al. (2006) where this abundance ratio, inferred in every star from the same line of Si I, at 3905 Å, changes systematically from about +0.7 to 0.0 dex as T_{eff} increases from 5000 to 6500 K for a sample of very metal-poor red horizontal branch stars and red giants. Presumably $[Si/Fe]$ is approximately the same for all the stars included in this figure, but some unrecognized systematic error has crept into the analyses so as to produce the strong trend they found for $[Si/Fe]$ with T_{eff} .

It must be recognized, however, that the recent analyses of bulge K and M giants have been carried out by several independent

groups, each of which contains highly experienced experts in this field. We therefore look for an explanation that allows both sets of deduced abundance ratios, those of the bulge giants and those found here for OGLE-2007-BLG-349S as well as for the other two well-studied microlensed bulge dwarfs, to be correct. Dredge-up and mixing in the giants is a possible culprit, particularly since Lecureur et al. (2007) found a large range in $[O/Fe]$, $[Na/Fe]$, $[Mg/Fe]$, and $[Al/Fe]$ among the most Fe-rich stars in their large sample of bulge giants. However, at least in the globular cluster case at low $[Fe/H]$, one sees C burning into N, and sometimes O burning into N as well (Cohen et al. 2002), occasionally with depleted Mg and enhanced Al. The signature of proton burning via the CN cycle, clearly seen in the globular cluster giants, is not apparent in the bulge giants. For this (and other) reasons, Lecureur et al. (2007) rejected mixing as the explanation for the large range they saw in some abundance ratios.

If larger samples of microlensed Galactic bulge dwarfs continue to show solar ratios of $[Mg/Fe]$ and $[Al/Fe]$ while samples of bulge giants show in the mean much higher values for each of these elements coupled with a large range for each, even at supersolar metallicity, we would suggest that the true initial abundance ratios for the light elements, including the α -elements, at high $[Fe/H]$ in the Galactic bulge are those of the dwarfs, not the giants.

8. SUMMARY

We have analyzed a high-dispersion spectrum of a microlensed dwarf, OGLE-2007-BLG-349S, in the Galactic bulge. The magnification of this event was very high, HIRES on the 10 m Keck I Telescope was used, the weather was clear with good seeing, and the exposure time was long compared to any previous such data, so the resulting spectrum has a relatively high signal-to-noise ratio.

We stress that in principle the abundance analysis of an upper main sequence dwarf is much easier and less prone to error for spectra of a fixed signal-to-noise ratio than that of a much cooler but much brighter bulge giant with a very complex spectrum full of blends and of strong molecular bands. The advantages of analyzing microlensed bulge stars, for which the required high signal-to-noise ratio can sometimes be achieved, for improving our understanding of the $[Fe/H]$ distribution and chemical evolution of the Galactic bulge are large.

We have derived for OGLE-2007-BLG-349S, which we believe to be a dwarf below the main-sequence turnoff with $T_{\text{eff}} \sim 5400$ K, a very high Fe metallicity, $[Fe/H] = +0.51 \pm 0.09$ dex. This is very peculiar given that many previous surveys of the metallicity distribution carried out with large samples of K or M giants in the Galactic bulge find both the mean and median $[Fe/H]$ to be subsolar. The two other highly magnified Galactic bulge dwarfs studied in detail, OGLE-2006-BLG-265S by Johnson et al. (2007) and MOA-2006-BLG-099S by Johnson et al. (2008), also have very high Fe metallicities.

In order to produce consistency, we suggest that there is a sampling bias in the bulge giant samples such that very metal-rich giants are strongly depleted. We suggest a physical mechanism for this; the very high mass loss rates expected for such metal-rich old giants can exhaust their envelopes prior to the normal He flash.

We also find that OGLE-2007-BLG-349S does not show enhancements of the α -elements; neither does OGLE-2006-BLG-265S, analyzed by Johnson et al. (2007). However, most bulge giants from samples with high-dispersion spectroscopy, e.g., the work of Fulbright et al. (2007) and particularly those from Lecureur et al. (2007), do show large (and varying from star to star) enhancements of $[Na/Fe]$, $[Mg/Fe]$, and $[Al/Fe]$, even at supersolar metallicities. We suggest that it is the abundances deduced for

the microlensed dwarfs that best represent the initial chemical inventory of the interstellar medium at the time these stars formed, while those derived for the bulge giants may not.

We recognize that three stars is a very small sample, but the implications of our results and inferences for the chemical evolution of the Galactic bulge and for the interpretation of integrated light spectra and broadband photometry of old simple stellar populations, such as luminous elliptical galaxies, are so important that we offer these hypotheses at this time.

The study of additional highly microlensed Galactic bulge dwarfs to increase the sample from just three such stars is clearly urgent. Now that ongoing microlensing surveys make such observations of Galactic bulge dwarfs feasible, we expect substantial improvements in the sample size of high-quality spectra for Galactic bulge dwarfs. Suitable high-magnification events are rare and lining up the necessary instruments/telescopes/clear weather at just the right time is difficult. Several years may be required to accumulate a suitable sample of spectra of highly microlensed dwarf stars in the Galactic bulge. We are now appropriately po-

sitioned to carry out such a time-critical program at the Keck Observatory over the next few years, and eagerly look forward to confirmation of our perhaps premature and provocative hypotheses in the not too distant future.

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APPENDIX

DIFFUSE INTERSTELLAR BANDS

The origin of the diffuse interstellar bands (DIBs) has been a puzzle for more than 30 years; see, e.g., the review by Herbig (1995). Most stars previously studied with high reddening are hot luminous young stars within a cluster embedded in a single cloud complex whose column density varies somewhat over the angular extent of the cloud, such as the IV Cyg association. But the reddening seen for OGLE-2007-BLG-349S [$E(B - V) = 0.68 \pm 0.10$ mag], while not particularly large, results from the many clouds along the line of sight to the Galactic center, and hence is much more representative of the typical ISM. Very little, if any, of this reddening is believed to arise within the Galactic bulge itself.

Because OGLE-2007-BLG-349S is a metal-rich cool dwarf, rather than an O or B star which would normally be used for such work, measurements of the DIBs are difficult and the results more uncertain than would arise for a much less complex hot star spectrum. The very strong and blended stellar absorption features in the blue part of the spectrum made a clear detection of the classical DIB at 4430 Å impossible. Parameters for those interstellar bands that could be detected with certainty are given in Table 5. They are comparable in strength with those observed for the well-studied B7 supergiant HD 183143, whose values are given in Table A1 of Herbig (1995), even though the reddening of this bright star is $E(B - V) = 1.28$ mag, about twice as large as that of OGLE-2007-BLG-349S. Snow & Cohen (1974) have shown that the band strength per grain in the line of sight apparently decreases with increasing grain size, such that dense interstellar clouds are less efficient in producing absorption by DIBs for the same total reddening than are less dense, but more numerous clouds in the line of sight. The very strong DIBs and immense interstellar absorption in the NaD lines in our spectrum of OGLE-2007-BLG-349S should further elucidate this “skin” effect.

TABLE 5
DIFFUSE INTERSTELLAR BANDS IN OGLE-2007-BLG-349S

Wavelength (Å)	FWHM (Å)	W_λ (mÅ)	Central Depth (%)
5778 ^a	9	1300	0.14
5778 ^b	1.8	330	0.19
6008.....	3.9	400	0.08
6282.....	4.3	2000	0.30
6611.....	1.5	200	0.14

^a Wide component of blend.

^b Narrow component of blend.

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