OGLE-2009-BLG-076S: THE MOST METAL-POOR DWARF STAR IN THE GALACTIC BULGE

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ABSTRACT

Measurements based on a large number of red giant stars suggest a broad metallicity distribution function (MDF) for the Galactic bulge, centered on [Fe/H] ≈ −0.1. However, recently, a new opportunity emerged to utilize temporary flux amplification (by factors of 100 or more) of faint dwarf stars in the Bulge which are gravitationally lensed, making them observable with high-resolution spectrographs during a short observational window. Surprisingly, of the first six stars measured, five have [Fe/H] > +0.30, suggesting a highly skewed MDF, inconsistent with observations of giant stars. Here we present a detailed elemental abundance analysis of OGLE-2009-BLG-076S, based on a high-resolution spectrum obtained with the UVES spectrograph at the ESO Very Large Telescope. Our results indicate it is the most metal-poor dwarf star in the Bulge yet observed, with [Fe/H] = −0.76. Our results argue against a strong selection effect disfavoring metal-poor microlensed stars. It is possible that small number statistics is responsible for the giant/dwarf Bulge MDF discrepancy. Should this discrepancy survive when larger numbers of Bulge dwarf stars (soon to be available) are analyzed, it may require modification of our understanding of either Bulge formation models, or the behavior of metal-rich giant stars.

Key words: Galaxy: bulge – Galaxy: evolution – Galaxy: formation – gravitational lensing – stars: abundances – stars: fundamental parameters

1. INTRODUCTION

The metallicity distribution function (MDF) of the Galactic bulge (hereafter, the Bulge) as measured by red giant stars has a long controversial history. In the 1980s and 1990s, studies of red giant stars in Baade’s window using low-dispersion spectroscopy showed that the Bulge MDF was quite metal-rich at [Fe/H] ≈ +0.2 (e.g., Whitford & Rich 1983; Rich 1988; Terndrup et al. 1990). Later, the mean metallicity was revised downward to [Fe/H] ≈ −0.25 by the first high-resolution study of K giant stars in Baade’s window by McWilliam & Rich (1994). Since then, results based on high-resolution spectroscopic studies of several hundred giant stars in or around Baade’s window suggest that the Bulge MDF peaks slightly below solar metallicity at [Fe/H] ≈ −0.1 (Fulbright et al. 2006, 2007; Cunha & Smith 2006; Cunha et al. 2007, 2008; Rich & Origlia 2005; Rich et al. 2007; Lecureur et al. 2007; Zoccali et al. 2003, 2008). However, the recent progress in observing low-luminosity dwarf stars in the Bulge while they are being optically magnified during gravitational microlensing events appears to give markedly different results and have re-ignited the debate over the Bulge MDF. So far, detailed elemental abundances based on high-resolution spectroscopy for a total of six microlensed dwarf stars and subgiant stars have been published (Johnson et al. 2007, 2008; Cohen et al. 2008, 2009; Bensby et al. 2009). Five of these six stars have high supersolar metallicities in the range +0.25 < [Fe/H] < +0.55 and it is only OGLE-2008-BLG-209S that is somewhat metal-poor at [Fe/H] = −0.32 (Bensby et al. 2009). The average metallicity from the six microlensed Bulge stars is [Fe/H] ≈ +0.29, which is 0.4 dex higher than the MDF obtained from giant stars.

OGLE-2008-BLG-209S is not just the only one of the six microlensed stars that turned out to be metal poor but also the only one that turned out to be slightly evolved, with stellar parameters placing it on the subgiant branch. This led Cohen et al. (2009) to speculate that OGLE-2008-BLG-209S is an exception to the rule, and that it should perhaps be excluded from the microlensed stellar sample. The average metallicity would then rise to [Fe/H] = +0.41, i.e., even more discrepant when comparing to the giant star MDF.

As microlensing events have no preference of picking source stars with a particular metallicity, observing enough events should provide an unbiased estimate of the Bulge MDF. So far, the microlensing events that have been observed in the Bulge lie at approximately the same angular distance from the Galactic center as the red giant stars in Baade’s window. Hence, there is no reason to expect that their MDFs should differ. By randomly picking six stars, 40,000 times, from the Zoccali et al. (2008) sample of giant stars, Cohen et al. (2009) found that in only 0.4% of the cases, the randomly drawn red giant sample was as metal-rich as the sample of microlensed dwarf stars. The question was then: which of the two tracers gives the correct picture: giant stars or the microlensed dwarf stars?

In this Letter, we present first results from a detailed abundance analysis of OGLE-2009-BLG-076S, the source star of another microlensing event toward the Bulge. We focus here on the metallicity, the α-elements Mg, Si, and Ti, the stellar age, distance, and the star’s kinematic properties. The full analysis and results for other α-elements, light elements, iron-peak elements, r-, and s-process elements, will be presented in an upcoming paper.

* Based on observations made with the European Southern Observatory telescopes, Program ID 082.B-0453(B).
2. OBSERVATIONS AND DATA REDUCTION

On 2009 March 21, the OGLE early warning system\(^7\) (Udalski 2003) identified OGLE-2009-BLG-076S as a possible high-magnification microlensing event toward the Bulge at \((l, b) = (1.2, -2.5)\) deg. Since the intrinsic source flux (inferred from the microlensing model) indicated that the star was a dwarf star we triggered our ToO observations, without knowing the color of the star, with the ESO Very Large Telescope (VLT) on Paranal. Due to the limited visibility of the Bulge in March, the target had to be observed toward the end of the night. Hence, OGLE-2009-BLG-076S was observed during the early morning hours beginning March 26 (MJD: 4916.29099), a few hours after peak brightness (see Figure 1). At maximum, the light from the source star was amplified by a factor of 68. Using the UVES spectrograph (Dekker et al. 2000), located at VLT UT2, configured with dichroic number 2, the target was observed for a total of 2 hr, split into four 30 minute exposures. The resulting spectrum was recorded on three CCDs with wavelength coverage between 3760–4980 Å (blue CCD), 5680–7500 Å (lower red CCD), and 7660–9460 Å (upper red CCD). A 1″ slit width yielded a spectral resolution of \(R \approx 45,000\).

The data were reduced with the most recent version of the UVES pipeline. The typical signal-to-noise ratio (S/N) per pixel at 6000 Å in the lower red CCD is \(~30\) (compare Figure 2). In the spectrum from the blue CCD, the S/N was, however, too low to allow secure identification of spectral line features or accurate measurement of equivalent widths. Hence, the spectral region blueward of 5680 Å was not used in the analysis.

Before the observation of the main target, we observed HR 6141, a rapidly rotating B2V star, at an airmass similar to what was expected for the Bulge star, to divide out telluric lines in the spectrum. We also obtained a solar spectrum, by observing the asteroid Pallas, that was used to normalize the elemental abundances in OGLE-2009-BLG-076S to those in the Sun. The S/N per pixel at 6000 Å in the solar spectrum and the B star spectrum is \(~350\) and \(~500\), respectively.

Examples of the Bulge star spectrum and the solar spectrum are shown in Figure 2.

\(^7\)http://ogle.astrouw.edu.pl/ogle3/ews/ews.html

3. ANALYSIS

3.1. Stellar Parameters from Spectroscopy

The determination of stellar parameters and calculation of elemental abundances were done in the very same way as in Method 1 of Bensby et al. (2009), wherein full details of the analysis can be found, which is based on equivalent width measurements and one-dimensional LTE model stellar atmospheres calculated with the Uppsala MARCS code (Gustafsson et al. 1975; Edvardsson et al. 1993; Asplund et al. 1997). The line list is an expanded version of the line list of Bensby et al. (2003, 2005) and is fully given in T. Bensby et al. (2010, in preparation.). The effective temperature \((T_{\text{eff}})\) is determined by requiring excitation balance of abundances from Fe\(i\) lines, the microturbulence parameter \((\xi)\) by requiring balance of abundances from Fe\(i\) lines versus the reduced equivalent width \((\log(\text{EW}/\lambda))\), and the surface gravity \((\log g)\) from ionization balance between abundances from Fe\(i\) and Fe\(II\) lines.

Due to shorter wavelength coverage and lower S/N only a fraction of the \(\sim250\) Fe\(i\) and \(\sim30\) Fe\(II\) lines available in the above-mentioned line list could be measured and utilized in the analysis. Hence, based on 57 Fe\(i\) and 7 Fe\(II\) lines we find that OGLE-2009-BLG-076S has \(T_{\text{eff}} = 5877\) K, \(\log g = 4.30\), \(\xi = 1.61\) km s\(^{-1}\), and an absolute Fe abundance of \(\log \epsilon(\text{Fe}) = 6.82\), or \([\text{Fe/H}] = -0.76\).

3.2. Uncertainties

The errors in the stellar parameters are of standard nature, and we estimate them to be of the same magnitude as in Bensby et al. (2009), i.e., \(\sigma T_{\text{eff}} = 200\) K, and \(\sigma \log g = 0.2\). These errors will introduce a random error of 0.12 dex in \([\text{Fe/H}]\) (see Table 6 in Bensby et al. 2009). Further, the standard deviation around the mean Fe\(i\) abundance is 0.10 dex. The corresponding formal error \((\sigma/\sqrt{N})\) in the mean Fe abundance is 0.013 dex, which is negligible in comparison to the effects that the uncertainties in the stellar parameters have on \([\text{Fe/H}]\). Hence, we estimate that the total error in \([\text{Fe/H}]\) is 0.12 dex.

3.3. Microlensing Techniques

Using microlensing techniques (Yoo et al. 2004), based on \(V\) and \(I\) data taken with the SMARTS 1.3 m telescope at CTIO, OGLE-2009-BLG-076S is estimated to have an intrinsic color of \((V-I)_{0} = 0.69 \pm 0.05\), i.e., similar to the Sun, and an absolute magnitude of \(M_{V} = 4.76 - 5 \log(d_{L}/d_{\text{jump}}) \pm 0.07\). The last term originates from the fact that the microlensing technique...
assumes that the source star (S) lies at the same distance as the
clump stars, in which case this term would vanish. The color–
$T_{\text{eff}}$ calibration by Ramírez & Meléndez (2005) then implies that
the effective temperature should be 5670 K. This is 200 K lower
than the “spectroscopic” temperature that we derive. However,
if the true temperature of OGLE-2009-BLG-076S is lower, the
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if the true temperature of OGLE-2009-BLG-076S is lower, the
abundances derived from the Fe I lines will also be lower, making
the star even more metal poor.

4. PROPERTIES OF OGLE-2009-BLG-076S

4.1. Evolutionary Status

The values of the effective temperature and surface gravity
demonstrate that OGLE-2009-BLG-076S is a true dwarf star. Utilizing
the fundamental relationship between surface gravity, effective
temperature, bolometric magnitude (see, e.g., Equation (4) in Bensby et al. 2003), we find an absolute mag-
itude of $M_V = 4.61$, which is in reasonable agreement with the value
based on microlensing techniques. Plotting the star on top of
the Yonsei–Yale isochrones (Yi et al. 2003; Kim et al. 2002;
Demarque et al. 2004) we find an age of $11 \pm 4$ Gyr, for OGLE-
2009-BLG-076S, (see Figure 3). This old age is consistent with
Bulge stars being an old population (e.g., Feltzing & Gilmore 2000), and is similar to what is found for thick disk
stars at the same metallicity (e.g., Bensby et al. 2005, 2007). From the
evolutionary tracks of Yi et al. (2003) we find that OGLE-2009-
BLG-076S has a mass of $\sim 0.9 \, M_\odot$.

4.2. Radial Velocity

From the spectrum we measure a heliocentric radial velocity
of $+128.7 \, \text{km s}^{-1}$ for OGLE-2009-BLG-076S, which should
be compared with the observed mean and standard deviation
of Bulge stars toward this direction, $+27 \pm 110 \, \text{km s}^{-1}$ (Zhao
1996; Howard et al. 2008). Hence, OGLE-2009-BLG-076S is consistent with Bulge kinematics.

4.3. Bulge Membership

Microlensed sources are not random Bulge sources, they are
heavily biased to come from more distant parts of the Bulge. This is because the lens must be in front of the source, and the probability of lensing is roughly proportional to the square root
of the lens-source distance. Most lenses are themselves in the
Bulge, particularly toward the direction where the integrated
density of Bulge sources is extremely high.

Furthermore, the event is at $(l, b) = (1.2, -2.5)$ deg, i.e.,
350 pc below the Galactic center. In this direction, the Bulge
(which is flattened by a factor of $\sim 0.6$) has an effective width of
600 pc. Beyond this range, its density falls off very rapidly (see,
e.g., the model by Han & Gould 1995, 2003). Hence, a random
source would have a very low probability of lying in front of the
red clump centroid.

Given the low probability of the source star being a foreground
disk star, that the measured radial velocity of OGLE-2009-BLG-
076S is consistent with the bulk of Bulge stars, that it has an old
age consistent with the Bulge being an old stellar population, it is
very likely that OGLE-2009-BLG-076S is a Bulge dwarf star.

4.4. Elemental Abundance Ratios

The abundances of OGLE-2009-BLG-076S were normalized
to those of the Sun (as determined from the Pallas spectrum)
on a line-by-line basis and then averaged for each element. The
absolute iron abundance measured in Section 3.1 is then equal
to $[\text{Fe/H}] = -0.76$.

Figure 4 shows three $[\alpha/\text{Fe}]$ abundance ratios in OGLE-2009-
B LG-076S compared to the average abundance ratios for thick
disk stars in the metallicity range $-0.86 < [\text{Fe/H}] < -0.66$ and
to Bulge giant stars in the metallicity range $-1 < [\text{Fe/H}] <
-0.3$. Compared to the Bulge giant stars, OGLE-2009-BLG-
076S shows the same degree of Mg and Ti enhancements, while
it has a lower enhancement in Si. Compared to the thick disk
dwarf stars, OGLE-2009-BLG-076S has similar enhancements
in all three elements, with a hint of being slightly more enhanced
than the median thick disk. These $\alpha$-to-iron overabundances at
$[\text{Fe/H}] = -0.76$ indicate a period of intense star formation in
the Bulge where chemical enrichment mainly is due to massive
stars, exploding as core-collapse supernovae. Furthermore, the
solar-type abundance ratios $[\alpha/\text{Fe}] \approx 0$ for the other five
microlensed dwarf stars at super-solar metallicities (Bensby et al. 2009; Johnson et al. 2007, 2008; Cohen et al. 2008, 2009) is consistent with the drop in $\alpha$-enhancement above solar metallicity observed in giant stars (compare Figure 10 in Bensby et al. 2009).
5. DISCUSSION AND CONCLUSION

OGLE-2009-BLG-076S is the currently most metal-poor dwarf star in the Bulge for which a detailed elemental abundance analysis based on high-resolution spectroscopy has been performed. It has a metallicity of \([\text{Fe/H}] = -0.76\), \([\alpha/\text{Fe}]\) abundance ratios consistent with in situ Bulge giant stars, and an old age of 11.5 Gyr. This result demonstrates that the Bulge does indeed contain metal-poor dwarf stars, as predicted by the presence of metal-poor giant stars, and that it is possible to observe them while they are being gravitationally micro lensed.

The now seven micro lensed dwarf and subgiant stars in the Bulge have an average metallicity of \([\langle \text{Fe/H} \rangle = +0.12\) (using \([\text{Fe/H}]\) values from Bensby et al. 2009 for the first four events). A two-sided Kolmogorov–Smirnov test with the giant stars from Zoccali et al. (2008) gives a very low probability that the MDFs from the dwarfs and the giants are the same (see Figure 5).

There are essentially three possibilities to explain the giant/dwarf Bulge MDF discrepancy. (1) Due to systematic errors in either giant or dwarf metallicity measurements, the identical underlying MDF appears different. Cohen et al. (2009) discuss this, including the size of the required errors, and find it very unlikely that the analysis methods are faulty. (2) The dwarf and the giant MDFs are different and have been correctly measured to be different. The discrepancy is caused by mass loss (as discussed by Cohen et al. 2009), or is due to different spatial distributions and chemical inhomogeneities in the Bulge. (3) The dwarf and giant MDFs are identical, but small number statistics for the dwarf stars happen to make them look different. (4) Or there may be some other unknown mechanism.

The new results for OGLE-2009-BLG-076S favor a combination of (2) and (3). While the giant star MDF is well defined, it could also be, as suggested by Cohen et al. (2008) that the most metal-rich giant stars lose their entire envelope before reaching the RGB tip. Hence, the most metal-rich giants are missing, and the MDF is somewhat shifted to lower \([\text{Fe/H}]\). This in combination with the small sample, perhaps too small to be representative of the Bulge MDF, of now seven micro lensed stars: five very metal-rich dwarf stars; one subgiant star just below solar metallicity; and one metal-poor dwarf star, make the difference between the giant star MDF and the MDF from the sample of micro lensed stars too large. However, with OGLE-2009-BLG-076S, we have shown that metal-poor dwarf stars exist in the Bulge, and that, if enough micro lensing events are observed, the differences between the giant and dwarf MDFs could in principle diminish to a level where the differences are only due to the effects of mass loss of the most metal-rich giant stars.

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