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Composition of the Galactic Bulge

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Abstract

We present detailed abundance results for 9 Galactic bulge stars in Baade's Window, based on HIRES (R=45,000–60,000) spectra taken with the Keck I telescope.

The alpha elements show non-uniform enhancements relative to the solar neighborhood trends: Mg and Si are enhanced in all our bulge stars by $\sim$0.5–0.3 dex, showing a slight decrease with increasing [Fe/H]. Oxygen is enhanced in most bulge stars, similar to the Galactic halo, but the [O/Fe] ratios suddenly decline beginning at [Fe/H]=–0.5 dex, with a slope consistent with no oxygen production in the bulge for [Fe/H]$\geq$−0.5 dex. The observed production of magnesium in the absence of oxygen synthesis appears to be inconsistent with current predictions for supernova nucleosynthesis yields; we suggest that this may be connected to the Wolf-Rayet phenomenon, which occurs in the pertinent metallicity range. The trend of [Ti/Fe] shows an enhancement relative to the solar neighborhood of $\sim$0.3 dex, but declines somewhat by solar metallicity; thus, the Ti trend is less extreme than found by McWilliam & Rich (1994, MR94). For metal-poor bulge stars calcium is enhanced by $\sim$0.3 dex, similar to the Galactic halo, but in our bulge stars with [Fe/H]$\geq$−0.5, Ca show a slight deficiency relative to the solar neighborhood value, consistent with the findings of MR94; this may indicate a slightly top-heavy IMF as suggested by MR94 and McWilliam (1997). Aluminum is enhanced in all our Galactic bulge giant stars by $\sim$0.25 dex; we argue that this is consistent with nucleosynthesis dominated by type II supernova events (SNII), implied by the Mg and Si enhancements.

The trend of the r-process element europium with [Fe/H] is similar to the [Ca/Fe] trend with metallicity, suggesting that the site of the r-process is associated with low-mass SNII, thought to be the dominant producers of calcium. The odd-Z element Mn shows approximately the same trend with [Fe/H] as seen in the solar neighborhood; this argues that the solar neighborhood trend is not due to Mn over production in type Ia supernova events (SNIa).

1.1 Introduction

We have been engaged in a long term program to study the composition of stars in the Galactic bulge, with the aim of constraining the conditions of the bulge's formation and chemical evolution at a level of detail that is impossible to obtain with any other method. Our plan is to obtain high S/N, high resolution spectroscopy for samples of >20 stars in each of 3 latitudes in the bulge: Baade's Window (b=–4°), Sgr I (b=–2.65°), and the Plaut field

(b=−8°). The Baade's Window sample was obtained using the HIRES spectrograph (Vogt et al. 1994) at the W.M. Keck Observatory. We have completed observations of Plaut's field using the MIKE spectrograph at the Magellan telescope, and we hope to complete Sgr I in 2004. We also plan to use the fiber mode of the MIKE spectrograph to obtain single-order spectra for 200 giants in each of these bulge fields. This will enable the homogeneity of the chemical properties of the bulge to be investigated, which may reveal evidence of galactic accretion, or multiple star formation events. Pertinent questions might include: What are the metallicity and composition gradients in the Galactic bulge, and how do they constrain bulge formation scenarios. Did some fraction of the population form in separate systems that merged very early on? What fraction of the population might have originated in a system similar to the Sagittarius dwarf spheroidal galaxy? Are there correlations between kinematics and composition, and do the composition gradients differ from the iron abundance gradient?

The fossil record of the Local Group is important because we cannot trace, with certainty, the evolution of any individual galaxy or galaxy population to the present epoch. In order to understand the formation of galaxies such as our own we must also use the constraints available from the ages, kinematics, and chemistry of stars in its constituent stellar populations. This is especially true if present day galaxies accumulated through a complicated set of mergers, as suggested in the CDM galaxy formation scenarios (e.g. Kauffmann 1996). K giants provide useful probes for understanding chemical evolution, because they are luminous, cover the full range of possible ages, contain lines from many elements, and except for a few light elements they preserve the composition of the gas from which they were formed. The widely accepted paradigm (Tinsley 1979) is that yields of massive star Type II SNe are enriched in alpha elements (e.g. O, Mg, Si, Ca, Ti), and the longer-timescale Type I SNe are enriched in iron. Consequently, the relative importance of alpha elements and iron gives a constraint on the enrichment timescale for the stellar population. For example, Elmegreen (1999) models bulge formation as a maximum intensity star burst that concludes in 10^8 yr. The consequences for chemical evolution are modeled by Matteucci, Romano, & Molaro (1999), which predicts abundance trends in the bulge for a wide range of elements. The expectation is that the rapid formation of the bulge should produce an over enhancement of alpha elements. However, all elements are of interest because different families of elements are thought to be made under a variety of astrophysical circumstances, which can provide information on the bulge environment during its formation, and may also lead to a greater understanding of nucleogenesis. Surveys of large samples of stars in globular clusters and dwarf spheroidal galaxies are just beginning, and the proposed research will add the bulge population.

1.1.1 A Brief History of Abundance Analysis for Bulge Giants

The earliest efforts to obtain spectra of bulge stars with linear detectors were by Whitford & Rich (1983) and Rich (1988). These studies concluded that there is a range of metallicity in the bulge, and there is evidence for super-metal-rich stars. Rich's (1988) mean abundance for the bulge was [Fe/H]$\sim$0.2. McWilliam & Rich (1994, MR94) obtained marginal high-resolution echelle spectroscopy (R=17,000, S/N$\sim$50) of 11 bulge K giants, from the sample of Rich (1988), using the CTIO Blanco telescope, and revised the abundance distribution in the bulge downward. The results of MR94 indicated a mean [Fe/H]=−0.15, and enhancements of the alpha elements Mg and Ti, even for stars with the solar iron abundance. The alpha elements Si and Ca did not appear to be enhanced over the solar neighborhood trends, and this was explained by MR94 in the context of the supernova nucleosynthesis predictions of Woosley & Weaver (1995, WW95), as due to a top-heavy bulge IMF. These early studies were made difficult by the lack of accurate basic optical and infrared photometry for the bulge, and the large, but uncertain, reddening (now known to be highly variable). The high metallicity and cool temperatures of the bulge giants also posed difficulties due to blending, and because it was necessary to use lines with somewhat uncertain gf values. In addition, the extreme stellar crowding in these low-latitude fields, and the faintness of the bulge stars, made it impossible to obtain the highest quality data with 4m-class telescopes; as a result, the use of relatively low resolving power spectra resulted in considerable blending with CN lines.

The first spectrum of a bulge giant with Keck (Castro et al. 1996) confirmed the metal-rich end of the MR94 abundance distribution; however, the spectrum was of low S/N and it was clear that a serious Keck telescope campaign was urgently needed. This effort has been underway since August 1998. Acquisition of the spectra has proceeded slowly, since we require $S/N > 50$ and $R > 45,000$; in fact, most of our spectra have $R = 60,000$.

An analysis of a subset of the new Keck spectra was given in Rich & McWilliam (2000, RM00). The analysis employed model atmosphere parameters based entirely on the spectra rather than on photometry: effective temperatures were set by demanding that Fe I line abundances were independent of excitation potential, whilst the stellar gravities were chosen so that Fe I and Fe II abundances were equal. The RM00 abundances at the metal rich end are $\sim$0.15 dex more metal rich than MR94. The key results of MR94 were confirmed for the alpha elements: [Mg/Fe] and [Ti/Fe] are elevated, while Ca followed the disk abundance trend. Oxygen was measured cleanly for the first time, and it was found that [O/Fe] declines rapidly above [Fe/H]=−0.5, a result that we confirm with the new work presented here. One problem with the RM00 study was due to the sensitivity of the spectroscopic model atmosphere parameters the adopted gf values of the iron lines. In addition, the covariance between the spectroscopic temperature and gravity meant that a slight error in temperature returned an error in gravity, which then required an additional adjustment in temperature, in the same direction as the original error. Thus, it was possible to obtain spectroscopic parameters unexpectedly far from the true values.

In the present study we have employed two spectroscopic methods for estimating stellar parameters, and we check these with V−K colors derived from the newly available 2MASS K-band magnitudes together with the V-band measurements from the OGLE microlensing survey. These three methods provide excellent agreement in the stellar parameters, so we are confident that the present study currently provides the best approach for the detailed abundance analysis of bulge giants. Our results for the iron abundance scale now returns more closely to that of MR94, and we give new results on abundance trends for other elements including some quite puzzling results for oxygen.

1.2 Observations and Data Reduction

Target bulge red giants were selected from the list of Arp (1965), MR94 and Sadler, Rich & Terndrup (1996). The spectra for this work were accumulated using the Keck I telescope and HIRES echelle spectrograph, over a period from 1998 to 1999 (the complete dataset includes additional observations and will be discussed by Fulbright, Rich & McWilliam 2004, in preparation). For most bulge stars the HIRES C1 decker was chosen,

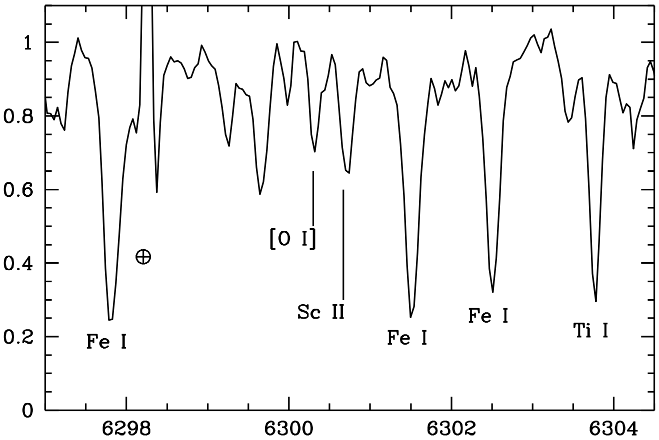

Fig. 1.1. Keck HIRES spectrum of BW I-039 (8000 sec exposure). Notice the clean, unblended, line of radial velocity-shifted [O I] 6300Å. The high resolution, at R=60,000, clearly resolves crucial lines, thus permitting abundance measurements for lines on the linear portion of the curve of growth.

giving a resolving power of R=45,000; however, the most metal rich stars were observed using the B2 slit, giving R=60,000. Typical S/N ratios were 50:1 per extracted pixel. The HIRES 2048^2 CCD enabled a wavelength coverage of $\lambda\lambda$ 5400–7800Å; although, roughly half of this range did not fall on the CCD. Because of the incomplete wavelength coverage it was necessary to select the spectral region carefully, in order to include the most important lines.

The spectra were extracted using *makee*, a pipeline reduction program written by T.Barlow. We preferred not to use the *makee* output normalized by the quartz lamp, because the result gave an unacceptable, very non-uniform, flattened spectrum. This failure was likely due to the difference in illumination afforded by the quartz lamp compared to the stars. Instead, we chose to use pixel-to-pixel flat fielding of the quartz lamp, but the echelle blaze function was determined from a fit to the continuum of a metal-poor star of similar temperature to the program stars. This resulted in an improved flattening; however, the results sometimes showed residual artificial modulation, so it was necessary to find the standard star spectrum which gave the flattest result. We are not sure why this problem occurred, but we suspect that the HIRES field rotation and atmospheric dispersion correction optics imposed a modulation of the stellar flux. This difficulty could impose systematic effects on our spectra, which would go unnoticed for metal-rich stars, which have little continuum. In Figure 1 we show sample reduced spectra.

Equivalent widths (EWs) of lines of interest were measured using the semi-automated program *GETJOB*, written by A.McWilliam (McWilliam et al. 1995). The basic line list was taken from MR94, with additional lines from Smecker-Hane & McWilliam (2004). We note that lines blended in MR94 were often unblended in the present spectra, due to the significantly higher spectral resolution.

1.3 Analysis

We used the LTE spectrum synthesis program MOOG (Sneden 1973) and the grid of LTE model atmospheres from Kurucz (1993) to compute abundances from the measured EWs. The line list came from MR94, with additional lines added for the increased wavelength coverage; complete details will be made available in a later paper. For Eu and Mn discussed here we included hyperfine splitting in the abundance calculations; the gf value and hfs parameters for the Eu II line at 6645Å came from Lawler et al. (2001), while the parameters for the Mn I lines are discussed McWilliam et al. (1995), McWilliam & Smecker-Hane (2004, in progress), and a later paper. For the [O I] line at 6300Å we employed the gf values adopted by Allende Prieto, Lambert & Asplund (2001), and include their Ni I blend at 6300.339Å. For consistency we re-derived the LTE solar oxygen abundance by matching the EW of the line in the Kurucz, Furenlid & Brault (1984) solar atlas, and found ϵ(O)=8.71; this is only 0.02 dex higher than the solar value of Allende Prieto et al. (2001) who employed a 3-dimensional time-dependent hydrodynamical model solar atmosphere in LTE.

1.3.1 Model Atmosphere Parameters

A long-standing difficulty for the study of Galactic bulge stars has been the paucity of good photometry, useful for the estimation of stellar effective temperature (T_{eff}); even V-band photometry of bulge K giants was in a poor state until the advent of the OGLE project (e.g. Paczyński et al. 1999). Although bulge reddening maps have been compiled (e.g. Stanek 1996) there is a significant variance in reddening over small spatial scales (Frogel, Tiede & Kuchinski 1999). An additional complication is that the OGLE V–I colors differ from solar neighborhood stars (e.g. Stutz, Popowski & Gould 1999; Kubiak et al. 2002). Given these difficulties we felt it prudent to investigate T_{eff} values derived using spectroscopic techniques.

The RM00 work employed Fe I excitation and Fe I/Fe II ionization equilibrium to determine T_{eff} and log g respectively; they obtained atmosphere parameters and [Fe/H] values significantly higher than found by MR94. The parameter change from MR94 was exacerbated by the covariance of the spectroscopic temperatures and gravities: an increase in T_{eff} led to an increase in log g, which resulted in an additional T_{eff} increase.

For Arcturus Smecker-Hane & McWilliam (2004, SM04) found a disconcerting 110K difference between the physical T_{eff} (based on the known flux, distance and angular diameter) and T_{eff} based on Fe I excitation (T_{ex}). This difference was reduced to 40K if a group of high-excitation Fe I lines was excluded from the analysis, and suggests problems with the Fe I gf values, or blends, at red wavelengths. The remaining 40K difference may be due to problems with the upper layers of the model atmospheres, where the empirical T-τ relation for Arcturus (Ayres & Linsky 1975) differs significantly from the Kurucz (1992) model (see also McWilliam et al 1995b).

In addition to excitation temperatures SM04 employed Fe ionization equilibrium to determine spectroscopic temperatures; this was made possible by fixing the gravity at the physical value (based on the distance and a mass estimated from color-magnitude diagram and theoretical evolutionary tracks). The resultant ionization temperature (T_{ion}) is likely more robust

Table 1.1. *Galactic Bulge Star Atmosphere Parameters*

Star	$[Fe/H]_{lines}$	T_{eff}	logg	$[Fe/H]_{model}$	ξ (km/s)	T_{eff}(V−K)
I–194	−0.09	4210	1.9	−0.1	1.04	4170
I–202	+0.02	4200	1.6	+0.0	1.50	4229
I–322	−0.12	4190	1.6	−0.1	1.50	4176
II–166	−1.60	5010	1.4	−1.6	1.59	...
III–152	−0.32	4190	1.8	−0.4	1.19	4171
IV–003	−1.28	4500	1.5	−1.3	1.43	4431
IV–072	+0.28	4250	1.9	+0.3	1.42	...
IV–167	+0.35	4360	2.0	+0.4	1.54	4305
IV–203	−1.22	3920	0.5	−1.2	1.75	3833
IV–329	−0.84	4300	1.5	−0.9	1.35	4165

than the excitation temperature, because the slope of abundance with excitation is more sensitive to individual erroneous points than the average of the Fe I or Fe II abundances. To compute ionization temperatures the stellar gravities must be determined independently; the required ingredients for this are the distance, reddening, observed flux and assumed masses. We note that α elements are important electron donors in the atmospheres of red giants, so the [α/Fe] ratios should be taken into account in the calculation of ionization temperatures. The lesson learned from Arcturus is that excitation temperatures are sensitive to systematic gf value errors and blends; this is likely more severe for stars more metal-rich than Arcturus.

For the bulge stars analyzed in the present work we computed both excitation and ionization temperatures. We also derived T_{ex} and T_{ion} with abundances taken relative to Arcturus, on a line by line basis; this ensured that gf value uncertainties did not affect the result. For the bulge K giants systematic errors due to problems with the Kurucz (1992) model atmospheres, and line blends, will partially, or completely, cancel when normalized Arcturus (a K0 giant), and lead to more reliable excitation temperatures. For the ionization temperatures we employed physical gravities based on the observed luminosity and temperature, computed using the dereddened OGLE-II V-band magnitudes (Paczyński et al. 1999), a distance of 8.0Kpc (e.g. Merrifield 1992, Carney et al. 1995), and an assumed mass of $0.8M_{\odot}$.

Our adopted stellar atmosphere parameters are listed in Table 1. Since completing the current abundance work the 2MASS near-IR catalog has been released for the Baade's Window field, which enables temperatures to be computed from the robust V−K color-temperature calibration of Alonso et al. (1999, 2001). In Table 1 we include the V−K temperatures, for comparison with the spectroscopic values, computed assuming the Paczyński et al. (1999) V-band extinction values and the reddening law of Winkler (1997). We note that the Paczyński et al. (1999) (V−K) reddening corrections are typically 0.18 magnitudes less than the value adopted by MR94 (from Frogel, Whitford & Rich 1984); this would result in effective temperatures $\sim$100K cooler from the Paczyński et al. photometry. The mean difference between spectroscopic and (V−K) temperatures, for the 7 stars in Table 1, is 49K, with a standard deviation about the mean difference of 50K; thus, the two temperature scales are in good agreement.

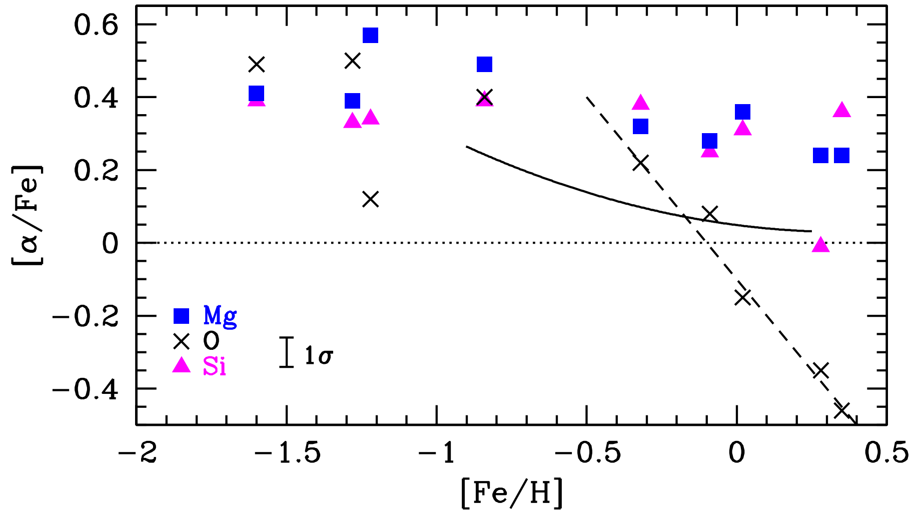

Fig. 1.2. The trend of alpha elements [Mg/Fe] (filled squares), [Si/Fe] (filled triangles), and [O/Fe] (crosses), versus [Fe/H], in the Galactic bulge. The solid line represents the [α/Fe] trend of Edvardsson et al. (1993). The dashed line indicates the locus of constant [O/H] above [Fe/H]=–0.5 dex.

1.4 Abundance Results and Discussion

The [Fe/H] results from the current work are only 0.03 dex, on average, higher than found by MR94, with a dispersion about the mean difference of 0.21 dex. If the current work and MR94 contribute equally to the dispersion each has a characteristic uncertainty of 0.15 dex; however, the errors are probably larger for the MR94 analysis. The RM00 [Fe/H] values were 0.14 dex higher than MR94; thus our sample is 0.11 dex lower than the RM00 metallicity scale. The difference between the current work and RM00 is due to our improved method for determining spectroscopic model atmosphere parameters, which is less prone to systematic errors than the classical method employed by RM00.

In Figure 2 we show the abundance ratios for 3 α-elements: O, Mg and Si. The [Mg/Fe] and [Si/Fe] ratios appear enhanced at $\sim$0.3 dex at all bulge [Fe/H], similar to the values seen in the halo, and well above the Edvardsson et al. (1993) trend of [α/Fe] for local disk stars (solid line in Figure 2). These enhancements in Mg and Si suggest that SNII played a dominant role in the synthesis of the elements at all [Fe/H] in the bulge, and that the bulge formed rapidly (e.g. Matteucci et al. 1999). The result confirms the Mg enhancement found by MR94, but differs from their claim of an apparently normal [Si/Fe] trend with [Fe/H]. Given the superiority of the current spectra, and analysis methods, we put greatest weight on the current Si results.

Figure 2 show that the oxygen abundances are enhanced by $\sim$0.4 dex for bulge stars with [Fe/H]$\leq$–0.8, similar to the values seen in the Galactic halo, but slightly higher than the non-oxygen α-element enhancements most metal-poor disk stars of Edvardsson et al. (1993). The figure also shows a strong decline in [O/Fe] with increasing [Fe/H] for bulge stars with [Fe/H]$\geq$−0.5; the slope is consistent with no production of oxygen above [Fe/H]=–0.5 (indicated by the dashed line).

It is significant that the sharp decline in [O/Fe] is not seen in [Mg/Fe], because both Mg and O are thought to be produced mostly in massive SNII events. Slightly enhanced [Mg/O] ratios are seen in some thin disk stars observed by Bensby et al. (2003), but the difference is smaller than found here. The SNII yields of WW95 predict an increased production of oxygen relative to magnesium with increasing progenitor mass; but in no case is Mg produced without O. One might appeal to metallicity-dependent yields and the Wolf-Rayet effect to understand the bulge O/Mg production; certainly, the Wolf-Rayet phenomenon affects massive SNII progenitors near [Fe/H]=–0.5. Qualitatively, one might expect greatly reduced hydrostatic oxygen production if the masses of the SNII progenitors is significantly reduced by Wolf-Rayet winds. However, predicted nucleosynthesis yields of exploding Wolf-Rayet stars by Woosley, Langer & Weaver (1995) indicate solar O/Mg ratios. Thus, we are unable to explain the observed halt in oxygen production at [Fe/H]=–0.5, and put it forward as a challenge for nucleosynthesis theorists.

If the [Fe/H] distribution of Sadler, Rich & Terndrup (1996) is taken at face value, then 80% of the Baade's Window stars are more metal-rich than [Fe/H]=–0.5, the point where oxygen production in the bulge stopped.

In Figure 3 we show plots of [Ti/Fe], [Ca/Fe] and [O/Fe] with [Fe/H]. The [Ti/Fe] ratio is enhanced in most bulge stars by $\sim$0.3 dex, similar to the Galactic halo; at metallicities greater than solar the general level of the Ti enhancement is uncertain, but appears reduced. In a very careful study Reddy et al. (2003) indicate that [Ti/Fe]$\sim$0.0 for the thin Galactic disk, roughly 0.1 dex lower than the Edvardsson et al. (1993) trend; thus, if we compare our [Ti/Fe] ratios with the Reddy et al. results the bulge appears enhanced at all [Fe/H]. This conclusion is similar to, but weaker than, the the Ti enhancements found by MR94, and suggests that SNII played a more important role in bulge nucleosynthesis than for the disk; however, since the nucleosynthesis of Ti is not well understood the conclusions which can be drawn are limited.

The [Ca/Fe] trend found here is similar to that found by MR94: for [Fe/H]$\leq$−0.8 [Ca/Fe] is halo-like, being enhanced by $\sim$0.3 dex; but the ratio is significantly reduced for more metal-rich stars. In our sample the average [Ca/Fe] ratio for stars with [Fe/H]$\geq$−0.5 dex is sub-solar, in contrast to the observed enhancement in [Mg/Fe] and [Si/Fe]. These observations are remarkably similar to the high [Mg/Fe] and low [Ca/Fe] ratios found for giant elliptical galaxies, with abundances measured from integrated-light spectra (e.g. Worthey 1998; Saglia et al. 2002), which supports our finding and suggest an evolutionary similarity between bulges and giant ellipticals.

Our bulge [Eu/Fe] values are compared to the disk and halo results from various studies in Figure 4. In the solar system composition the abundance of Eu is consistent with a 97% r-process fraction. Europium is often reported as being an r-process element, by virtue of its large neutron capture cross section. We note that large [Eu/Fe] enhancements can occur via the s-process, but in this case the enhancements of Ba, La and other strongly s-process elements will be even greater; RM00 showed that the [Ba/Eu] ratio for bulge stars is consistent with the halo mixture, dominated by the r-process. Like the halo the metal-poor bulge stars show a $\sim$0.4 dex enhancement in [Eu/Fe], and is consistent with the notion that Eu, like α elements, are produced by SNII events. For the more metal-rich bulge stars, [Fe/H]$\geq$−0.5, [Eu/Fe] appears roughly constant near the solar value. The most metal-rich

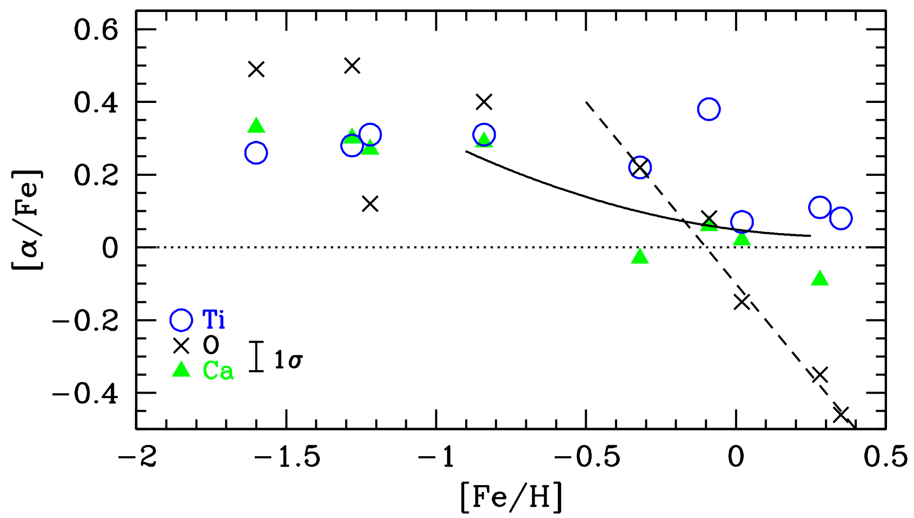

Fig. 1.3. The trend of alpha elements [Ca/Fe] (filled triangles), [Ti/Fe] (open circles), and [O/Fe] (crosses), versus [Fe/H], in the Galactic bulge. Lines are same as in Figure 2. The [Ca/Fe] trend is close to the solar value for [Fe/H]$\geq$−0.5 dex.

bulge star in this sample, IV 167, may be enhanced by $\sim$0.2 dex; but this could possibly be due to a contaminating blend, most likely from CN, with the Eu II line at 6645Å. It is notable that the [Eu/Fe] trend does not seem to continue declining, as seen in the solar neighborhood disk stars. The [Eu/Fe] ratio appears flat with [Fe/H] in the metal-rich bulge stars; in this regard Eu behaves more like Ca than the other α-elements, which suggests a connection in the formation of these two elements. Since theoretical nucleosynthesis yields (e.g. WW95) indicate that Ca is produced mainly by low-mass (15–25 $M_{\odot}$) SNII progenitors the similarity between the [Eu/Fe] and [Ca/Fe] trends suggests that it is in this mass range that the r-process is most important. Current theoretical predictions have not yet identified the source of the r-process, so our observations of the bulge composition is of special interest. In this regard it is particularly important to measure the abundances of r-process and α-elements in different galactic environments, as the correlations may yield information on the r-process site.

Our results for [Al/Fe] are shown in Figure 5, and compared to the solar neighborhood results of Chen et al. (2000) and the Sagittarius dwarf spheroidal galaxy from Smecker-Hane & McWilliam (2004). It is clear that the value of [Al/Fe] is sensitive to the galactic environment, and appears to be enhanced in more rapidly evolving systems; this is consistent with the production of Al in SNII events, as expected from nucleosynthesis theory. Our mean [Al/Fe] ratio, at +0.25 dex is identical to the results of Reddy et al. (2003) for thick disk stars in the Galaxy. This supports our findings for the bulge, which like the thick disk, is thought to have formed on a rapid timescale. A plot of [Al/Mg] versus [Fe/H] does show a slope, qualitatively in agreement with expectations of metallicity-dependent yields from SNII (e.g. Arnett 1971). Near [Fe/H]=−1 the bulge [Al/Mg] ratio is very similar to the predictions of WW95; however, the observed bulge slope of [Al/Mg] with [Fe/H], at $\sim$0.12 dex/dex, is

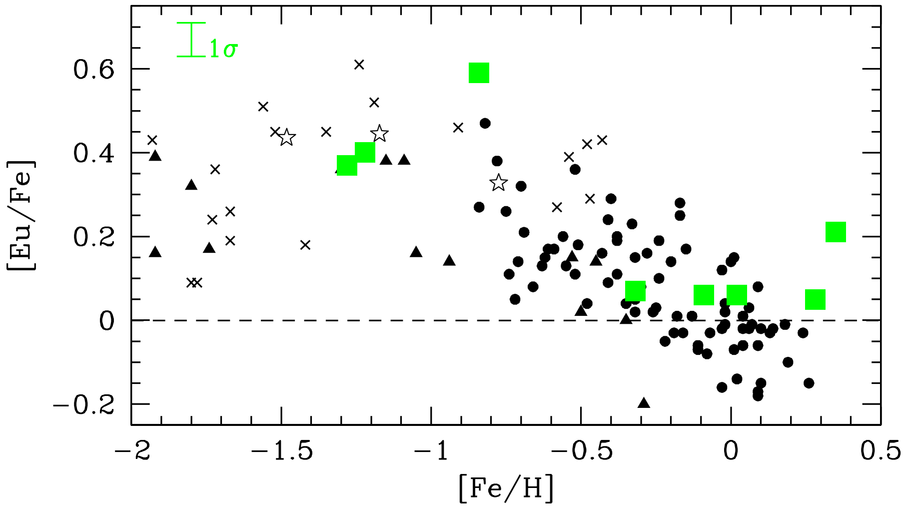

Fig. 1.4. The trend of the r-process neutron-capture element europium with [Fe/H] (large filled squares) for stars in the Galactic bulge. Results for the disk and halo are shown for comparison: filled circles from Woolf, Tomkin & Lambert (1995), filled triangles from Gratton & Sneden (1994), and crosses from Shetrone (1996); open stars indicate the mean values for globular clusters M71, M13, M5, and M92 from Shetrone (1996).

much shallower than the value of ∼0.35 dex/dex indicated in the calculations of WW95. At solar [Fe/H] the WW95 predictions for [Al/Mg] are ∼0.25 dex higher than our bulge observations. Part of the discrepancy is likely due to the unusual composition of the bulge, which complicates the comparison between WW95 and our observations.

Our enhanced [Al/Fe] ratios are unlikely to be related to the enhancements seen in some globular cluster red giant stars (e.g. see Sneden, Ivans & Fulbright 2004, this conference). The globular cluster enhancements, due to proton burning, are characterized by large star-to-star differences, unlike the roughly constant [Al/Fe] values seen in the bulge; also unlike the bulge, the globular cluster Al enhancements are accompanied by depletions of oxygen. Furthermore, the general consensus is that globular cluster Al enhancements are associated with high stellar density, because no field stars have been found with abundance patterns associated with Al-enhancement in globular clusters; although the bulge appears crowded, its density is far below that of globular clusters.

In Figure 6 our abundance trend of [Mn/Fe] with [Fe/H] is shown, and compared to the solar neighborhood results, with data from numerous studies (see McWilliam, Rich & Smecker-Hane 2003); it is clear that Mn behaves similarly in the bulge and solar neighborhood. The observed increase in [Mn/Fe] above [Fe/H]∼−1 appears entirely consistent with the nucleosynthesis predictions for SNII by WW95.

Our bulge Mn abundances are not consistent with the notion that the Mn trend in the solar neighborhood is due to Mn over-production by SNIa, as proposed by Gratton (1989). Gratton noted that the form of [Mn/Fe] relation with [Fe/H] appears as the inverse of the trend of

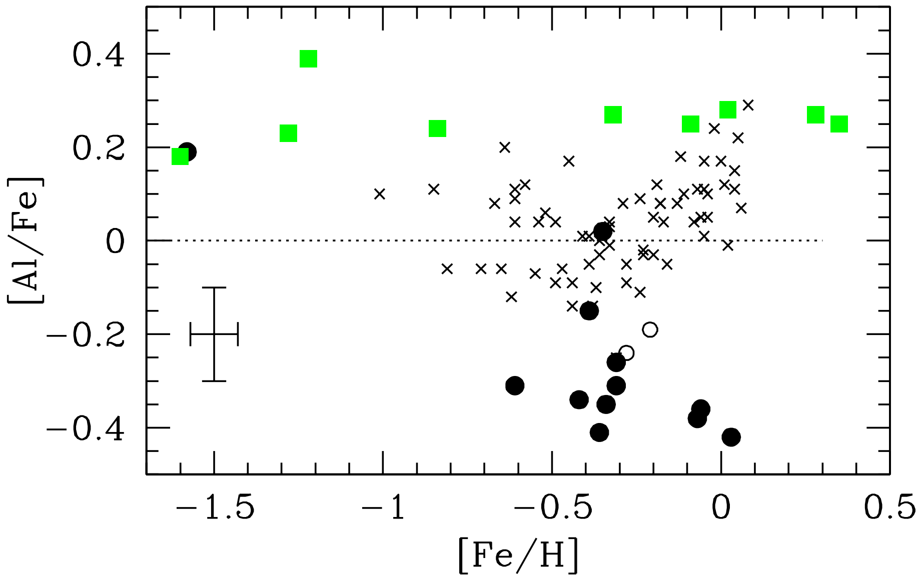

Fig. 1.5. A comparison of [Al/Fe] for stars in the Galactic bulge (filled squares), the solar neighborhood (crosses from Chen et al. 2000), and the Sagittarius dwarf spheroidal galaxy (filled circles from Smecker-Hane & McWilliam 2004; open circles from Bonifacio et al. 2000); clearly, [Al/Fe] depends upon galactic environment.

α-elements with metallicity, and proposed that the increase in [Mn/Fe] was due to the onset of SNIa, which produce excess Mn. If the Gratton scenario were correct, then systems like the bulge, characterized by rapid formation, with little time for significant nucleosynthesis by SNIa, would show deficient [Mn/Fe] ratios compared to the solar neighborhood trend. Our conclusion against the Gratton scenario is supported by deficiencies in [Mn/Fe] seen in the Sagittarius dwarf spheroidal galaxy (McWilliam et al. 2003).

It is of value to compare our results with the composition found for stars in the bulge globular cluster NGC 6528, by Carretta et al. (2001, C01): Both studies indicate general enhancements of α-elements, but C01 find Ca enhanced by $\sim$0.2 dex, whereas we find no Ca enhancement above [Fe/H]$\sim$−0.5. To investigate this difference we computed abundances from the published C01 equivalent widths and atmosphere parameters; our calculations show good agreement for Fe lines, but $\sim$0.2 dex deficiency in [Ca/Fe] relative to the sun; thus, either C01 included a sign error, or their analysis led to the different result. We note that the Ca lines in C01 are strong enough to be quite saturated, and thus the abundances are quite dependent on the treatment of the microturbulent velocity. The low Ca/Fe result found in this paper include stars more metal deficient than C01, with more lines on the linear portion of the curve of growth, and less likely to suffer from problems with microturbulent velocity. We note that C01 found enhanced [Na/Fe], similar to the [Al/Fe] result reported here; it is entirely expected that Na should follow Al when Al is produced by SNII, as we propose. Our bulge results do not confirm the low [Mn/Fe] found by C01 for NGC 6528, despite the

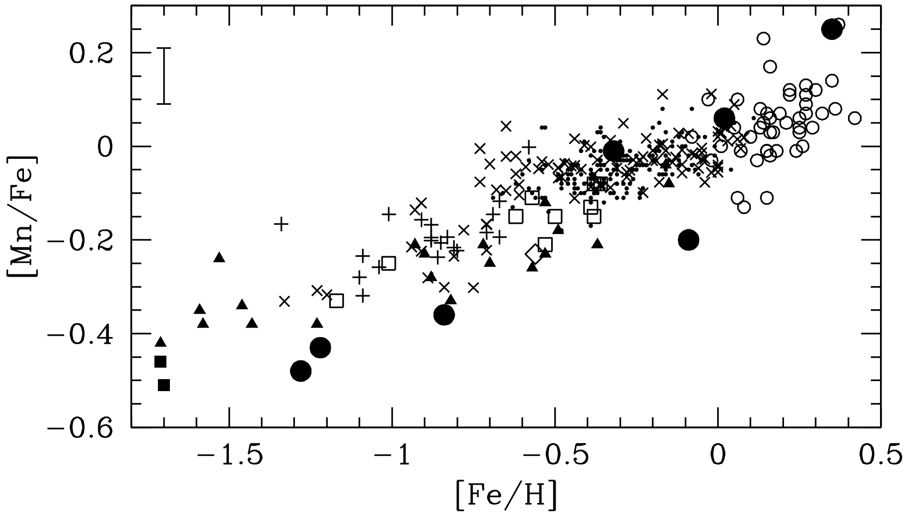

Fig. 1.6. The trend of [Mn/Fe] with [Fe/H] in the galactic bulge stars (large filled circles) compared to the solar neighborhood (see McWilliam et al. 2003 for the list of sources). The bulge points approximately follow the solar-neighborhood trend; large deficiencies might be expected if Mn is over-produced in type Ia supernovae, as suggested by Gratton (1989).

inclusion of Mn *hfs* treatment; if this difference is confirmed then NGC 6528 evolved in a very different manner than the Galactic bulge. Low [Mn/Fe] near solar [Fe/H] for NGC 6528 could occur if the cluster were formed from the ejecta of many metal-poor SNII, resulting in low, halo-like, [Mn/Fe] at higher than halo [Fe/H].

1.5 Conclusions

We find that the alpha elements Mg, Si and Ti are enhanced in the Galactic bulge, consistent with nucleosynthesis by type II supernovae, even at solar metallicity. Oxygen is enhanced in the metal-poor bulge, but above [Fe/H]∼–0.5 the [O/Fe] ratio declines steeply, with a slope consistent with no oxygen production. The decline in [O/Fe] without a similar decline in [Mg/Fe] is a challenge for supernova nucleosynthesis theory. We naively suggest that the onset of the Wolf-Rayet phenomenon may be connected to the cessation of oxygen production in the bulge.

The alpha element Ca and the (mostly) r-process element Eu are enhanced in the metal-poor bulge, but lie near the solar value at metallicities above [Fe/H]=–0.5. The low calcium abundances are similar to the composition of giant elliptical galaxies and might be understood as due to a paucity of low-mass SNII progenitors, due to a top-heavy IMF. The similarity of the [Eu/Fe] and [Ca/Fe] trends suggest a connection in the formation of these two elements, indicating that the r-process occurs mainly in low-mass SNII. The correlation of r-process and alpha element abundances presents an interesting way to constrain the site of the r-process, which should be exploited further.

The [Al/Fe] ratio is enhanced in the Galactic bulge, similar to results for the thick disk, and is consistent with Al over-production in rapidly evolving systems. Although the [Al/Fe] ratio remains constant, near +0.25 dex, over a 2 dex range in [Fe/H], the [Al/Mg] ratio shows a small slope with [Fe/H] in approximate accord with supernova nucleosynthesis predictions of metallicity-dependent Al/Mg yields; however, the slope is much less than predicted by WW95. Thus, it would be interesting to see whether the observed [Al/Fe] enhancements and [Al/Mg] trend persist for metal-poor bulge stars well below [Fe/H]=−1.6, as a test for supernova nucleosynthesis models.

The iron-peak element manganese shows nearly the same trend with [Fe/H] as the solar neighborhood disk, in accord with the nucleosynthesis predictions of WW95. This trend would not be expected from scenario of Mn-overproduction in SNIa, which Gratton (1989) proposed to explain the observed solar neighborhood [Mn/Fe] trend with [Fe/H].

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