Abundances of Stars in the Galactic Bulge Obtained Using the Keck Telescope

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ABSTRACT

We report on detailed abundances of giants in the Galactic bulge, measured with the HIRES echelle spectrograph on the 10-m Keck telescope. We also review other work on the bulge field population and globular clusters using Keck/HIRES. Our new spectra have 3 times the resolution and higher S/N than previous spectra obtained with 4m telescopes. We are able to derive $\log g$ from Fe II lines and excitation temperature from Fe I lines, and do not rely on photometric estimates for these parameters. We confirm that the iron abundance range extends from $-1.6$ to $+0.55$ dex. The improved resolution and S/N of the Keck spectra give [Fe/H] typically 0.1 to 0.2 dex higher than previous studies\textsuperscript{1} for bulge stars more metal rich than the Sun. Alpha elements are enhanced even for stars at the Solar metallicity (as is the case for bulge globular clusters). We confirm our earlier abundance analysis of bulge giants\textsuperscript{1} and find that Mg and Ti are enhanced relative to Ca and Si even up to [Fe/H]=+0.55. We also report the first reliable estimates of the bulge oxygen abundance. Our element ratios confirm that bulge giants have a clearly identifiable chemical signature, and suggest a rapid formation timescale for the bulge.

Keywords: Stellar Abundances, Galactic Bulge, 8-10m Telescopes, Stellar Populations

1. INTRODUCTION

Because of their faintness, reddening, severe crowding, and high metallicity, the stars of the Galactic bulge remained among the last Galactic population to be studied with high resolution spectroscopy. In the scientific cases for large telescopes, the goal of successfully defining the abundances and chemistry of bulge stars has often figured prominently. Of course, the real driver for studying these stars is not the technical challenge, rather it is their potential to yield insights into the formation of bulges and ellipticals.

Within the last five years, the combination of spectroscopy with the Keck telescopes and imaging with the Hubble Space Telescope has revolutionized the study of galaxies at high redshift. A population of plausible progenitors to present-day $L^*$ galaxies has been discovered at $z > 3$ and a proposed star formation history\textsuperscript{2} of the Universe has been sketched out. However, these observations cannot trace the evolution of the $z > 3$ galaxies into their present-day counterparts. In many respects, such as luminosity and clustering, they strongly resemble the progenitors of present-day luminous galaxies. It is also possible to constrain the formation time of bulges from observations of galaxies at $z \leq 1$. Recent pixel-by-pixel analysis\textsuperscript{3} of resolved images of high redshift galaxies with clearly visible bulges apparently shows that at any given redshift, bulges are bluer than the reddest galaxies of elliptical morphology. Unfortunately, this imagery cannot easily distinguish between a late starburst on top of an old population versus a mostly intermediate-age population. So it is valuable to seek other available evidence, such as the ages and abundances of stars in the Galactic bulge.

The exact agreement between HST luminosity functions of old metal rich globular clusters, and NTT luminosity functions of the Galactic bulge field\textsuperscript{4} strongly suggests that the bulge formed early and rapidly. HST photometry in a number of different bulge fields also shows that the stars brighter than the oldest turnoff point are foreground stars associated with the disk, not the bulge.\textsuperscript{4} Age constraints from luminosity functions or the luminosity of the main sequence turnoff point, while powerful, are only accurate to (at best) $\approx 1 - 2Gyr$. The detailed composition

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of stars in the bulge does not constrain the absolute age of the bulge. However, it does constrain the timescale for chemical enrichment, and it helps to relate the bulge (or not) to elliptical galaxies. As a larger sample of stars is accumulated, more detailed theoretical inferences about the enrichment history will be possible.

The bulge of the Milky Way is a clearly distinct population, as defined by the classical characteristics of a stellar population, age, abundance, kinematics, and structure. The central 1000 pc of our galaxy is dominated by old, metal rich stars with very high phase space density. The stellar mass of the bulge is $2 \times 10^{10} M_\odot$, roughly 1/3 that of the disk, but it still accounts for a large fraction of the baryonic mass of the Galaxy. The image of the bulge obtained using the DIRBE instrument on board the COBE satellite dramatically illustrates its distinct nature and its similarity to more distant ellipticals. It is possible to develop a model that both fits the surface brightness in the COBE image, solves Poisson’s equation, and gives stellar orbits that reproduce the observed kinematics of the bulge.

Presently, there is no clear consensus on the ages and formation timescales of bulges in general. The colors of bulges imaged in detail in the optical and IR by HST are consistent with very large ages, a result first found in 1969 for the bulge of M31. On the other hand, the integrated Mg line strengths of bulges are less than those of ellipticals at the same iron line strengths, which would argue that bulges might have experienced a less intense and more extended period of star formation than the ellipticals.

1.1. How Element Ratios May Constrain the Formation of the Bulge

The motivation for measuring abundance ratios in old stars is that they preserve the fossil record of the early star formation process. Potentially, the initial mass function, star formation rate, and importance of infall or extended star formation at late times can all be recovered from abundance ratios. The material treated briefly below is discussed in more detail elsewhere. Scenarios for forming the bulge predict a wide range of timescales, from $\sim 10^8$ yr for a violent starburst, to a few Gyr for a massive disk that thickens into a bar. The modeling of observed abundance trends can distinguish among these models.

![Figure 1](image)

**Figure 1.** A schematic plot of $[\alpha/\text{Fe}]$ vs $[\text{Fe}/\text{H}]$ in disk/halo stars. A shallower IMF slope (increasing number of massive stars) will enhance the alpha elements. A higher star formation (faster enrichment) will keep the alpha elements high, even above the Solar iron abundance.

**Metallicity:** The fundamental notion of chemical evolution is that other than those light elements produced in the Big Bang, metals are made in supernovae. Because SNe explode in $\sim 10^6$ yr and distribute their metals widely, it is possible to model the process as a simple differential equation (the Simple Model of chemical evolution). In the case of the bulge, the deep potential well and likely violence of the early starburst satisfy the model assumptions, and the abundance distribution fits the Simple Model. The yield is the ratio of the mass of metals produced to the total mass locked up in long-lived stars. In the Simple Model, the yield is the mean metal abundance of the population. The shallower the initial mass function slope (more massive stars) the higher the yield.

**Alpha Elements:** When the first 200-inch echelle spectra of metal poor stars and globular clusters were obtained, it was noted that some even-Z elements (O, Mg, Si, Ca, and Ti) were overabundant by $\sim +0.3$ dex relative to the Solar Neighborhood. These are the so-called $\alpha$-elements, although their actual synthesis is far more complicated than...
transmutation by successive capture of helium nuclei in massive stars. The widely accepted explanation for these over abundances is that massive star (Type II supernovae) dominated the enrichment at early times; models indicate that the ejecta of these SNe are very rich in alpha elements. Although type I SNe produce the iron peak elements, their contribution to the iron abundance becomes important only after \( \sim 1 \text{Gyr} \), as time is required for the formation of a prior generation of white dwarfs.

The diagnostic value of trends of \([\alpha/\text{Fe}]\) vs \([\text{Fe/H}]\) extend beyond their use as a crude clock, as has been suggested for the bulge. If the IMF is dominated by massive stars, the alpha elements can be enhanced by more than +0.3 dex, while a high star formation rate will result in stars of Solar iron abundance having an alpha-enhanced composition, as appears to be the case for the bulge. Finally, although Ti is observed to be elevated with the alpha elements, the nucleosynthesis calculations predict a low yield of Ti in massive stars; this remains a problem.

**Neutron-Capture Elements:** The two dominant modes of neutron capture also offer the potential to serve as clocks, and as a fossil record of early star formation. Supernovae (probably Type II) are believed to be the site of the r-process while the helium burning shells of AGB stars are suspected as the site of s-process production, as was shown in early calculations. The Ba/Eu ratio is is especially useful because it is sensitive to the r-process fraction of heavy elements. However, practical use of this diagnostic in the bulge is somewhat complicated by the lack of weak Ba lines, although La and Nd offer excellent possibilities as s-process indicators. Depending on whether [Ba/Eu] as a function of [Fe/H] approaches the s-process or the lower r-process value, one can infer either a disk-like or halo-like (Type II SN ejecta dominated composition) star formation history. In principle, evidence for r-process nucleosynthesis indicates the presence of enrichment due to Type II SNe which could be due either to a rapid burst of star formation or a shallow IMF. In the bulge, we hope to use [Ba/Eu] and other heavy element diagnostics to test the hypothesis that the bulge formed from gas initially enriched by the astrosynthesis of the halo. The heavy elements have tremendous potential to constrain the enrichment timescale (and stellar masses responsible) in great detail, especially in the difficult 1-5 Gyr regime. The production of stable isotopes of some s-process elements such as Rb turns out to be very sensitive to the temperature of the helium burning shells of AGB stars.

The derivation of abundances from the equivalent widths of the lines of heavy elements is done with caution. Each absorption line is split into multiple sub-components by nuclear hyperfine splitting; failure to account for this effect can lead to serious errors in the abundances.

Before turning to a discussion of our results, we point out that our program would not have been possible without the HIRES echelle spectrograph as well as the Keck telescopes. Just now, in the year 2000, we are seeing the successful first light of UVES at the VLT, and HDS at Subaru. HIRES paved the way for these successful instruments, at a time when the operational success of such an instrument on a 10m telescope was far from guaranteed.

### 2. Prior Work with Keck

The first major effort on high resolution spectroscopy of bulge giants was that of McWilliam & Rich (1994), which represents the limit of what may be accomplished with 4m-class telescopes. This work showed that the mean iron abundance in the bulge is \(-0.25\) dex, not the +0.3 dex found from the early low resolution spectroscopy. As we discuss later, the new Keck data may once again revise the abundance scale somewhat upwards. MR94 also found that the alpha elements behave in a peculiar manner. Mg and Ti are enhanced up to Solar metallicity, while Ca and Si follow a more disk-like enrichment trend. Also, MR94 found several stars with enhancements of the largely r-process element Eu, which is thought to be produced by type II SNe, consistent with the Mg over-abundances. One aim of the new 10m science is to test these findings.

MR94 found that the neutron-capture elements Ba, Y, Zr scale approximately with Fe in the solar ratios. Although these elements are also made by neutron-capture in massive stars, the bulk of the solar composition is from low-mass AGB star nucleosynthesis. Rapid bulge enrichment by massive stars would likely have excluded low-mass AGB stars from contributing s-process elements. A constraint on the bulge formation timescale is possible if the detailed heavy-element abundance patterns can be used to identify the role of low-mass AGB nucleosynthesis.

#### 2.1. Bulge Field Stars

The CTIO 4m data were S/N=40 and R=17,000, while the HIRES spectra range from R=45,000 to 60,000 for the most metal rich stars. The first goal after MR94 was to verify the surprising result that the most metal rich bulge giants have [Fe/H]=+0.44. As we mentioned earlier, Castro et al. (1996) analyses the spectrum of the bulge giant
BW 4167 using 3 different methods: spectrum synthesis, curve of growth, and classical equivalent width analysis using the spectrum synthesis code MOOG. The analysis was hampered by the S/N of the spectrum available, but still gave $[\text{Fe/H}]=+0.47$, and that the most metal rich bulge giant has the same line strength as the canonical metal rich disk giant, $\mu$ Leonis. Castro et al. largely confirmed the high end of the bulge metallicity scale found from the 4m data. Even considering the low S/N of these early data, the result is important as it was the first Keck spectroscopy of a bulge giant.

Echelle spectroscopy of bulge main sequence stars at $V > 20$ would appear to be beyond the grasp of the present generation of 8-10m telescopes. However, these stars are occasionally magnified by factors of 10 or more by microlensing events, and current surveys identify rising events with enough regularity that one can confidently schedule observing runs in the anticipation that amplified stars will be available to observe. Minniti has acquired KECK/HIRES spectroscopy of one such event in which microlensing boost enhanced the effective diameter of the Keck telescope to 15m. The capability to measure a dwarf star gives the first Li abundance constraint in the bulge; the Li abundance of $A(Li) = 2.25 \pm 0.25$ is slightly below that of the Hyades ridgeline. Although no conclusions can be drawn from this single measurement, the technique is important for two reasons. First, Li is of course destroyed in the course of stellar evolution. While Li rich giants are known (even in the bulge; our Keck spectra confirm the 180mA Li line found by MR94 in BW I-194), the source of Li in giants is widely thought to be nuclear reactions in the envelope and is of course not primordial. Second, red giants in globular clusters are established to undergo deep mixing, during which nuclear transmutation of certain alpha elements (O and Mg, but not Si, Ca, and Ti) may occur. A detailed abundance analysis of stars in NGC 6528 finds evidence for deep mixing, even in this cluster of approximately Solar metallicity. While deep mixing apparently does not appear to affect abundances of halo field giants, it is important to obtain spectra of dwarfs in the bulge to be certain that deep mixing is not affecting the derived abundances.

With microlensing surveys continuing, one may anticipate that the use of the microlens boost technique will be of increasing importance. However, one must obtain excellent spectra for each case, as once the microlensing event concludes, there is no opportunity to repeat the high-dispersion spectroscopy until the 30m - 100m telescopes of the future become available.

### 2.2. Bulge Globular Clusters

As observations have improved, our view of the globular cluster system toward the Galactic Center has changed. Early studies of the kinematics supported association of these metal rich clusters with a disk-like system. As larger samples of these obscured globular clusters were studied, it became apparent that the kinematics of these clusters more closely resemble the bulge stars. Recent kinematic studies uphold this view. Considering a new enlarged sample of these clusters, with distances, find that their spatial distribution and abundance distribution both follow the light of the Galactic bulge.

In contrast to the wide abundance range in the field, the bulge globular clusters are simple stellar populations, that is, having a very narrow range in age and abundances of their constituent stars. Therefore, abundance analysis of these clusters is especially valuable in understanding the more distant stellar populations in bulges and ellipticals which presently may only be studied in their integrated light. In these metal rich globular clusters, the stars at the tip of the red giant branch are so blanketed by TiO that their $V$ band magnitudes are fainter than those of the red clump. The giant branch thus has the form of an arc; even the $I$ band suffers some blanketing. The same giant branch morphology is seen in the field population of the bulge. Population synthesis models of stellar populations must include the correct giant branch. Because many stars on first ascent have strong TiO bands, the overall impact is to increase the TiO line strength in stellar populations. TiO bands are found throughout the spectrum, including overlapping the very important MgH feature at 5170Å (the basis of the Faber Mg$_2$ index). Excessively strong TiO in the giants potentially could contribute to a spurious measurement of enhanced Mg in elliptical galaxy populations. It is therefore very important to understand the underlying composition that gives rise to these descending giant branches, and the simple stellar populations of metal rich globular clusters are ideal for this.

The earliest abundance studies of two giants in NGC 6553 relied on spectra from the ESO 3.6m telescope. NGC 6553 has the classic descending giant branch arc, indicating near-solar metallicity; it lies 6kpc from the Sun and has the same turnoff to HB magnitude difference as is found in the extreme halo. The initial results are surprising: $[\text{Fe/H}]=-0.55$ and $[\alpha/\text{Fe}] = +0.6$ for a total $Z$ of Solar or greater. If correct, these findings would require a revision in our view of nucleosynthesis in metal rich populations, including elliptical galaxies.
Figure 2. This figure illustrates the spectrum of the most metal rich star in our sample \([\text{Fe/H}]=+0.55\) BW I-039, obtained with the HIRES spectrograph on the Keck 10m telescope. Notice the clean separation of OI 6300.3 from the Sc II line, which we achieve using \(R = 60,000\). This star is \(V = 17.5\) and was observed through a 0.56 arcsec slit.

However, a different result has been found from spectra obtained using Keck/HIRES. The greater aperture of Keck permits spectroscopy of hotter stars on the red horizontal branch. A team led by Cohen and Gratton analyze spectra of 5 RHB stars in NGC 6553 and 4 giants in NGC 6528. They find \([\text{Fe/H}]=−0.16\) and \([\text{Ca/Fe}]≈ +0.3\) for NGC 6553, and \([\text{Fe/H}]=−0.13\) with a similar alpha enhancement in NGC 6528. In contrast to our new HIRES spectroscopy of bulge giants which we report below, the effective temperature and gravities are derived from photometry and the distance to the clusters. However, the basic checks such as trend of iron abundance with excitation potential show that this has been a reasonable approach. In NGC 6528, Carretta et al. find star-to-star variations in O and Na are reminiscent of the deep mixing effects noted in other clusters. In particular, O and Na are anti-correlated. These results show that the two bulge clusters have composition and abundance similar to that of the bulge field stars at the same iron abundance.

The formation of globular clusters is clearly observed at the present epoch in merging galaxies. A simple analytic model in which globular clusters are tidally limited and experience disk and bulge shocking can account for the truncated mass distribution seen amongst the old Galactic globular clusters at the present time. Very likely, NGC 6528 and 6553 are survivors of the bulge’s ancient globular cluster population left over from its formation.

As the S/N of data improve, the derived abundances of metal rich stars frequently increase because the continuum is defined more clearly. The Keck’s aperture also enabled Cohen et al. to use red horizontal branch stars some 700K hotter than the 4000K cool red giants observed by Barbuy et al. Nonetheless, more work is called for on the bulge clusters and Keck, VLT, and Subaru will contribute toward this effort in the next year.

3. NEW RESULTS FOR THE BULGE K GIANTS FROM KECK/HIRES

We began our Keck/HIRES spectroscopy of bulge giants in August of 1998, with the aim of obtaining high S/N, high resolution spectra of 25 bulge giants with Keck/HIRES. Initially, we are reobserving a number of stars from our earlier study; these stars are located in Baade’s Window, a region of relatively low extinction in the Galactic bulge some 500 pc south of the nucleus, at \(l = 0^\circ, b = −4^\circ\). At a declination of \(−30^\circ\), the field is accessible from Mauna Kea for about 4 hours per night. For all but the most metal-rich stars a 0.86 arcsec slit is used, giving \(R \sim 45,000\). For the very metal-rich stars I−039 and IV−167 we used a 0.57 arcsec slit to obtain \(R \sim 60,000\). The data have been reduced using MAKEE, written by Tom Barlow at Caltech. This code has enabled us to semi-automatically fit all measurable lines with gaussian profiles, to obtain equivalent widths, which are then input to the MOOG spectrum synthesis code using the Kurucz 64 layer model atmospheres. Ultimately, we will synthesize small regions of spectra around each element of interest. Fig. 2 shows part of the spectrum near the...
Figure 3. Illustration of three spectra which cover most of the abundance range found in the bulge. BW IV-003 has $[\text{Fe/H}]=-1.24$, while BW I-194 has $[\text{Fe/H}]=-0.03$, and BW I-039, one of the most metal rich stars from Rich (1988) has $[\text{Fe/H}]=+0.55$. The resolution of BW I-039 is 60,000 while the other spectra are at $R=45,000$. We ultimately plan to synthesize the Mg region before deriving final abundances.

forbidden O I lines, for one of our faintest, most metal rich stars, BW I-039. In Fig. 3, we illustrate how the wide abundance range present in the bulge affects the spectra. Spectrum synthesis of most features will be required for stars exceeding the Solar iron abundance.

The higher resolution and greater wavelength coverage of the HIRES spectra offer many advantages over the MR94 study. In particular, the problems of line blending and the lack of continuum regions is greatly improved; this is especially important for the derivation of the oxygen abundance from the [O I] lines.

Even so, analysis of these spectra are complicated by the well-known problems of bulge stars. The alpha elements, especially Mg, are an important source of electrons in the atmospheres of K giants. Consequently, if $[\text{Mg/Fe}]=+0.4$, the $H^-$ continuous opacity increases relative to that for Solar composition. Therefore, use of simple model atmospheres with a scaled Solar composition will give element abundances that are spuriously low. If bulge giants contain excess CN (and this is very likely the case for the metal rich stars) the atmosphere boundary temperature may be reduced enough to cause serious deviations from the temperature structure of solar-neighborhood giants, and so affect the abundance derived from spectrum synthesis programs which adopt solar composition model atmospheres. One must use a grid of realistic model atmospheres, but also one must derive as many of the stellar parameters as possible from the spectra themselves.

The spectra have such good resolution and S/N that we are able to determine the gravity, microturbulence, effective temperature, and $[\text{Fe/H}]$ in a self-consistent analysis from the Fe I and Fe II lines. This is arguably more reliable than relying upon photometric measures for $T_{\text{eff}}$ and $\log g$ (e.g. MR94) because of the classic problems that have plagued analysis of bulge stars: large and spatially variable reddening, uncertainty in distance, and at the metal rich end, blanketed broad-band colors. Temperatures and microturbulent velocities were obtained by forcing the iron
abundance to be independent of excitation potential (Fig. 4) and equivalent width, respectively; the atmosphere gravities were adopted by requiring agreement between Fe II and Fe I abundances.

Figure 4. Excitation plot of iron lines as a function of excitation potential. This plot constrains the effective temperature, abundance, and gravity of BW I-194. Fe I lines are filled symbols; Fe II lines are the open squares. The Fe II line with the largest abundance appears to be blended. This star has $T_{\text{eff}} = 4360 \pm 100$ K, $\xi = 1.23 \pm 0.05$ km/sec, $\log g = 2.5$, $[\text{Fe} / \text{H}] = -0.03$

We find that the iron abundances are typically 0.1 to 0.2 dex higher, an average of 0.11 dex greater, in a sample of 6 stars in common with the MR94 sample. For example, I-194 was $-0.26$ dex, and we find $[\text{Fe} / \text{H}] = -0.03$. BW IV-072 was $-0.05$ dex in MR94, but the Keck spectra give $[\text{Fe} / \text{H}] = +0.25$. At the metal rich end, BW IV-167 was found in MR94 to be $+0.44$ dex, and this was confirmed in Castro et al. (1996). We find $[\text{Fe} / \text{H}] = +0.54$ dex for IV-167 and $+0.55$ dex for I-039, one of the most metal rich stars found in the Rich (1988) survey of 88 bulge K giants. It is noteworthy that Castro et al. took 3 approaches to the abundance analysis, and that the spectrum synthesis method gave $[\text{Fe} / \text{H}] = +0.55$ for BW IV-167. The analysis of our small sample suggests that the mean iron abundance of the bulge may increase from the $-0.25$ dex of MR94 to $-0.14$ dex. The upper limit of iron metallicity appears to be at $[\text{Fe} / \text{H}] = +0.55$, but obviously, we need a larger sample of stars at the metal rich end.

The increase in iron abundance derived from the higher quality spectra comes mainly from two sources: Most important is that our new continuum levels are higher, whereas MR94 could not detect the presence of weak line blanketing (mostly from CN). In the MR94 study, the CN blanketing had the effect of increasing derived abundances for the weak Fe I lines. This resulted in a higher microturbulent velocity for MR94, to force stronger Fe I lines into agreement with the weak lines; the Keck spectra yield microturbulent velocities of 0.57 km/s lower than MR94. The second factor is the adopted gravities: The photometric gravities of MR94 were lower than the present spectroscopic values by an average of $\sim 0.2$ dex, and in some cases, by as much as 0.6 dex. The error analysis of MR94 showed that a $+0.30$ dex increase in gravity gives $[\text{Fe} / \text{H}]$ higher by $+0.05$ dex.

Is this the final answer on the iron abundance? We are beginning to feel more confident, but we do plan to measure a large number of weak iron lines, to confirm our findings. Even at $R = 60,000$, the continuum is not always clearly found in the most metal-rich stars. We have not yet synthesized all 8,000 CN lines (as was done in MR94) but we will do so. Coincidences of some Fe I lines with the occasional CN line may bring the abundances of the most metal rich stars down slightly. However, we believe that we are converging on the correct answer, finally.
Figure 5. Derived trends of element ratios for stars in the Galactic bulge, from Keck/HIRES data. Left panel illustrates trends for Mg, Ti and O, while the right panel shows Ca, Si, and O. The solid line is the mean trend line for all alpha elements in Milky Way disk stars. For the first time, we find a bulge giant with enhanced O at [Fe/H]=0; a result that has been predicted but is now seen for the first time. Mg and Ti are clearly enhanced; the strong enhancement of Ti is not expected from models of supernova yields (see Fig. 6 below). Ca and Si follow trends that are more typical for disk/halo stars. Our results confirm the puzzling abundance trends in prior studies. Because we have not yet done molecular equilibrium calculations, we consider the oxygen results to be very preliminary.

3.1. Relative Abundances of the Alpha Elements

We now turn to the alpha elements, for which we report preliminary abundances. The final abundance analysis will employ spectrum synthesis for each line region. Returning to Figure 2, one can inspect the Mg lines to see why this is necessary, even for BW I-194 which has Solar abundance. Our abundances are based generally on 2-15 lines each of Ca, Si, and Ti, but we have only 1-3 usable Mg lines. The following results which are based on just the equivalent width measurements should be taken with caution. The oxygen abundances are from the 6300.3A forbidden line, but we consider these to be quite preliminary. We have not yet performed the requisite CNO equilibrium calculations, since we have not measured the carbon abundances in these stars. However, interesting trends are beginning to emerge in Fig. 5. MR94 found a peculiar behavior among the alpha-elements, that Ca and Si follow trends somewhat characteristic of the Solar neighborhood, while Mg and Ti are enhanced as would be expected for a stellar population enriched in a short timescale starburst. Analysis of our first 8 stars appears to confirm MR94. In fact, the effect appears to be even more extreme at the metal rich end, with O joining Ca and Si. One interesting new result is that two stars have [O/Fe]=+0.3 at [Fe/H] ≈ 0. This result was expected for the bulge and is now tentatively confirmed. Disk stars have Solar oxygen abundance at [Fe/H]=0.

It is very premature to even speculate on the cause of the peculiar trends among the alpha elements. However, the source of enrichment is supernovae, and we can turn to models of supernova yields in search of an explanation. The production factors in Fig. 6 were calculated as followed. First, the total mass of each element produced in the various SN models is the sum of the mass of all the stable isotopes of that element. Dividing the mass of each element by the mass of the SN ejecta gives the mass fraction of that element. The production factor for an element is the mass fraction of that element divided by the mass fraction of that element in the Sun. The production factors approximately indicate the enrichment of the ejecta relative to Solar composition. Fig. 6 shows that O and Mg should be preferentially produced in the most massive SNe, while Si and Ca are produced more copiously in 15-25M_⊙ stars. All of the models produce about the same amount of Ti; presently, there are no SNe nucleosynthesis calculations which are consistent with the observation that Ti is enhanced in the Galactic halo and bulge populations. Yet enhancement of Ti is certainly real and is seen, for example, in the metal rich globular cluster ([Fe/H]=−0.79) M71 at the level of +0.5 dex. The evident behavior of Ti as an alpha element remains a problem in the modeling of supernova yields.

The incorporation of SN yields and star formation rates into chemical evolution models gives increasingly detailed predictions of abundance trends; the latest of these efforts argues for a bulge enrichment timescale of ~ 0.5 Gyr.
Different progenitor masses are indicated by connected symbols; O and Mg are produced in the greatest quantities at high mass (∼35M⊙) but not in the lower mass (15–25M⊙) supernovae; the latter are responsible for most of the Si and Ca production. Note that these models predict no significant enhancement of Ti, contrary to observations of stars in the Galactic bulge and halo. The production factor is the ratio of the mass fraction of each element relative to the total mass of the SN ejecta, divided by the element’s mass fraction in the Sun.

However, the physical constraint on the formation timescale is the point at which Type I SNe begin to contribute the bulk of iron production, which depends on the as yet unknown mechanism for Type I SNe.

4. SUMMARY

In contrast to the well known achievements in the high redshift universe, the impact of Keck on stellar abundances is less widely known, yet significant. Keck/HIRES spectroscopy has placed the abundance scale of the bulge on a secure footing. We have just begun to tap the potential information in these spectra. Prior efforts at measuring the oxygen abundance in the bulge from data obtained on 4m class telescopes were ineffective. For the first time, we are beginning to see emerging some clear trends in oxygen as a function of iron abundance. The abundance range, and puzzling element trends found by McWilliam & Rich (1994) are confirmed.

Two metal rich globular clusters toward the bulge have also been the subject of a major campaign with HIRES. NGC 6553 and 6528 have been found to have Solar metallicity with the alpha elements of O and Ca enhanced. The compositions of their stars are precisely those of bulge field giants at the same metallicity. The formation of the proto-bulge probably proceeded much as is observed in starburst galaxies today, with the production of numerous star clusters, a few of the more luminous of which are observed to survive to the present day.

As spectroscopy of fainter stars becomes feasible, enrichment trends are now available for new stellar populations, such as dwarf spheroidal galaxies. As more high resolution spectra from large telescopes are analyzed, these trends
may become valuable in distinguishing the formation histories of stellar populations. The Sagittarius dwarf spheroidal galaxy (a tidally disrupted dwarf galaxy lying in the direction of the bulge) is the only dwarf companion of the Milky Way that contains stars as metal rich as the Sun. One might speculate that the bulge could have been built from the shards of a few such disrupted systems, and the presence of Solar metallicity stars in the Sgr dwarf strengthens this idea. However, the Galactic bulge and disk populations are dramatically different from the Sgr dwarf stars, which have subsolar Ca and Si abundances at $[\text{Fe/H}]=0$. The trends of Mn with $[\text{Fe/H}]$ and $[\text{Ba/Y}]$ with $[\text{Fe/H}]$ are even more different between the bulge and the Sag dwarf, and it is possible to explain these differences as being caused by early, rapid enrichment in the bulge. The origin of the metal rich population in the Sgr dwarf is an interesting problem in chemical evolution, given the low mass of that galaxy and its encounter with the Milky Way. We can pretty much rule out, however, that the metal rich population in the Sgr dwarf was somehow captured from the bulge, or that Sgr was once a much larger galaxy that enriched as quickly as the bulge did.

One may also compare the bulge composition to metal rich dwarf stars in the Solar neighborhood, which are $\approx 10$ Gyr old and reach the same high metallicities ($[\text{Fe/H}]=+0.55$). High resolution spectroscopy of these stars shows them to clearly have disk-like compositions: Mg, Ti, and O abundances are at approximately Solar values with no clear trends. In contrast, the old open cluster NGC 6791 has $[\text{Fe/H}]=+0.4$ and enhanced Ca. Chemical enrichment reaching high iron abundance evidently does not proceed the same way in all environments. Based on the compositions of stars, one clearly cannot produce the bulge out of the disintegrated remnants of systems like the Sagittarius dwarf spheroidal.

Qualitatively, the abundance pattern in the bulge strongly suggests rapid, early enrichment, consistent with the predictions of chemical evolution models. The notion of rapid enrichment agrees with other studies of the age of the stellar population in the bulge. The distinct nature of the bulge composition gives us confidence that abundance ratios offer a powerful diagnostic tool that may help to decipher the fossil record of galaxy formation.

Many open questions remain. The bulge has a bar-like morphology, and the most successful scenario for forming a bar-like bulge requires dynamical instabilities occurring in a pre-existing disk. However, N-body simulations of bars indicate that they are unlikely to survive for a Hubble time, yet the Galactic bulge is extremely old. Further, the extreme stellar density near the nucleus is evidence for strong dissipation being a factor in the formation of the Galactic bulge.

If the bulge abundance ratios favor a top-heavy IMF and very rapid formation, one must infer that ellipticals enrich more rapidly (and perhaps with a heavier IMF) because their Mg$_2$ indices at a given $<\text{Fe}>$ line strength are so much higher compared to the bulges; in fact spiral bulges lie near the lower range in Mg index in these diagrams. Before addressing these questions, and the challenge of relating the local data to high redshift observations, we plan to increase our sample size and explore the behavior of different atomic species. However, the study of the Milky Way bulge stars (and eventually, perhaps, individual stars in the bulge of M31) does have promise in illuminating the chemical evolution of ellipticals.

4.1. Looking Towards the Future

This year, two new powerful high dispersion spectrographs come on line. At the VLT UVES has already passed science verification and has produced beautiful data. The HDS spectrograph at Subaru is just about to see first light. Fiber feeds to UVES will enable the acquisition of as many as 8 stars in a single exposure covering all orders, or spectroscopy of over 100 stars in a single echelle order. The latter capability will be enjoyed by the new echelle spectrograph that will be commissioned next year on the Magellan I (Baade) telescope.

On Keck, the NIRSPEC infrared spectrograph can reach $R=30,000$ in the near-IR, and places old giants in the Galactic center within reach. We plan to extend our abundance studies to the field and cluster stars of the Galactic center in the next few years.

The hard reality remains that analysis of the data will still be time consuming. For metal rich stars, it is clear that even at $R=60,000$ we require a full spectrum synthesis before we can feel completely secure in our results. It will be a challenge to keep up with the flood of new data in the coming years. This situation should be an inspiration to observers and theorists alike, as we enter these unprecedented times.
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