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High-resolution Spectroscopy in the Galactic Bulge: The IR Perspective

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Abstract

Using the NIRSPEC spectrograph at Keck II, we have obtained high resolution, echelle spectra in the range $1.5-1.8$ μm of bright, cool giants in the Bulge globular clusters and in Baade's window. We present the results of the abundance analysis of several metals like Fe, C, O and other alpha-elements, by using full spectral synthesis techniques and equivalent width measurements. The clusters and field stars show oxygen enhancements at the level of +0.3 dex up to almost solar metallicity. These results are consistent with prior abundance studies for K giants and support a formation scenario in which the bulge forms rapidly.

1.1 Introduction

The early history of star formation and chemical enrichment of our Galaxy is imprinted in the abundance patterns of the old stellar populations: the halo, bulge, and thick disk (McWilliam 1997, ARAA, 35, 503; hereafter MW97).

According to the standard scenarios for chemical evolution, type II supernovae (SNe) with massive progenitors mainly enrich the interstellar medium with α–elements during the earliest phases of star formation. Iron–like elements and carbon are predominantly produced at later epochs by type Ia SNe and AGB stars, respectively, with low–intermediate mass progenitors. Only a complete analysis of the key abundance patterns can provide a correct description of the overall evolutionary scenario of a stellar system, being different elements synthesized in stars of different masses, hence on different timescales.

In halo/disk field stars the average [α/Fe] abundance ratio shows a general enhancement of 0.3–0.5 dex with respect to the solar value at [Fe/H]≈-1 and a linear decreasing trend towards solar [α/Fe] with increasing metallicity up to [Fe/H]≈0.0 (see Fig.3 by Wheeler, Sneden & Truran, 1989 and MW97). The actual position of the knee (i.e. the metallicity at which [α/Fe] begins to decrease) depends on the type Ia SN timescales and it is also a function of the Star Formation Rate (SFR), while the amount of α–enhancement depends on the Initial Mass Function of the progenitors of the type II SNe.

In globular clusters a mean [α/Fe]≈0.4 overabundance has been found but the trend with metallicity is not so well defined since the $[\alpha/Fe]$ measurements are still too incomplete in the high metallicity domain to draw any firm conclusion (see e.g. Kraft 1994; Carney 1996; Sneden, this conference).

The Galactic bulge remains relatively unexplored, for a variety of reasons. The high and variable foreground extinction fades red giants to 17 mag or fainter, making 8-10m telescopes essential for abundance analysis. Low latitude fields have severe crowding, and the extinction is essentially complete within 3° of the Galactic center. Finally, the brightest members have long been known to be late M giants, for which abundance analysis is essentially not possible in the optical due to severe molecular blending and blanketing effects.

The most accurate abundance determinations in the Galactic Bulge obtained so far and based on high resolution optical spectroscopy refer to a sample of K–giants in the Baade's window (McWilliam & Rich 1994, hereafter MWR94; Rich & McWilliam 2000, hereafter RMW00, McWilliam, this conference) and a few giants in two globular clusters, namely NGC 6553 and NGC 6528 (Barbuy et al. 1999; Cohen et al. 1999; Carretta et al. 2001).

It is thus obvious that, in order to study both the field and cluster Bulge population with the necessary statistical significance, it is crucial to extend the spectral analysis in the near infrared (IR) domain, where the reddening and blanketing effects are much less severe than in the optical. Moreover, the IR spectral range provides the highest sensitivity to the physical parameters of cool stars and the contrast between the red giants and the fainter Main Sequence population is greater than in any other optical passband, drastically reducing the crowding, even in the innermost core region of globular clusters.

1.2 Infrared Spectroscopy of Cool Giants

The near IR spectra of cool giants show many absorption features due to both neutral metals (Fe I, Ca I, Si I, Mg I, Ti I, Al I etc.) and molecules (CO, OH) which allow accurate abundance analysis in a wide range of metallicities up to the super–solar regime. It is worth mentioning that the IR CO and OH molecular bands provide the most robust estimates of Oxygen and Carbon abundances and their isotopic ratios in cool stars (cf. e.g Thompson et al. 1969; Thompson & Johnson 1974, Lambert et al. 1984, Wallace & Hinkle, 1996). Most of these molecular lines in the H band are not saturated and can be safely treated under the LTE approximation, being roto-vibrational transitions in the ground electronic state.

Oxygen is a key element to trace the chemical enrichment history in several astrophysical contexts. However, the determination of its abundance in giant stars is still controversial since the major UV and optical diagnostics yield somewhat different results. Systematic calibration off-sets, non-LTE effects and TiO and CN blends in the coolest giants can severely affect both the optical [O I] and O I–triplet lines and the electronic OH molecular transitions in the UV (see e.g. Meléndez & Barbuy 2001, Hill 2001), making IR roto-vibrational OH lines the most reliable diagnostics (see e.g. Balachandran & Carney 1996, Meléndez, Barbuy Spite 2001).

The direct measurement of the $^{12}C/^{13}C$ abundance ratio provide major clues on the efficiency of the mixing processes in the stellar interiors. The classical theory (Iben 1967; Charbonnel 1994 and reference therein) predicts a decrease of ^{12}C/^{13}C$\approx$ 40 after the first dredge–up, the exact amount mainly depending on the chemical composition and the extent of the convective zone. However, many sets of observations (see e.g. Suntzeff & Smith 1991, Shetrone 1996, Gratton et al. 2000 and references therein) on low mass field and cluster giants show much lower (^{12}C/^{13}C$\leq$10) isotopic abundance ratios compared to those expected from the *first dredge-up*, suggesting that some other non-standard mixing mechanisms should be at work during the ascent of the Red Giant Branch – RGB – (see e.g. Charbonnel 1995, Denissenkov & Weiss 1996, Cavallo, Sweigart & Bell 1998 and references therein, Boothroyd & Sackmann 1999).

The availability of NIRSPEC, a high throughput IR echelle spectrograph at the Keck

Observatory (McLean et al. 1998), allowed us to start a long–term project devoted to obtain accurate abundance measurements in a complete sample of both field and cluster giants of the Galactic Bulge.

1.3 Observations and Spectral Analysis

We have obtained high resolution NIRSPEC spectra of several giants in the core region of a sample of globular clusters and in the Baade's window, covering the range 1.5 – 1.8 μm, where most of the atomic and molecular lines of interest are concentrated. The high resolution echelle mode (R=25,000), with a slit width of 0.43$''$ (3 pixels) and a length of 8$''$ and the standard NIRSPEC-5 setting have been selected.

As an example, Fig. 1.1 shows the H band images of the observed core region of the Terzan 4 and Terzan 5 globular clusters taken with the slit viewing camera (SCAM) of NIRSPEC, which has a field of view of $46'' \times 46''$ and a scale of $0.183''$ $pixel^{-1}$.

The raw spectra of the observed stars have been reduced using the REDSPEC IDL-based package written at the UCLA IR Laboratory. Each order has been sky subtracted by using nodding pairs and flat-field corrected. Wavelength calibration has been performed using arc lamps and a 2-nd order polynomial solution, while telluric features have been removed by using an O-star featureless spectrum.

Synthetic spectra of giant stars for different input atmospheric parameters have been computed, using an updated version (see Origlia, Rich & Castro 2002, hereafter ORC02) of the code described in Origlia et al. (1993), which provides full spectral synthesis over the 1-2.5 μm range,

The code uses the LTE approximation and is based on the molecular blanketed model atmospheres of Johnson, Bernat & Krupp (1980) which have been extensively used for abundance studies based on high resolution spectra of cool stars (e.g. Lambert et al. 1984, Smith & Lambert 1985, 1990). For temperatures higher than 4000 K the ATLAS9 models are used. Since in the IR the major source of continuum opacity is H^- with its minimum near 1.6 μm, the dependence of the results on the choice of model atmosphere is much less critical than in the optical range.

Three main compilations of atomic oscillator strengths are used, namely the Kurucz database, Bièmont & Grevesse (1973, hereafter BG73) and Meléndez & Barbuy (1999). On average, the log-gf values from Meléndez & Barbuy (1999) are systematically lower than Kurucz ones but in most cases the difference does not exceed 0.2 dex and the overall scatter in the derived abundances is < 0.1 dex (see also ORC02 for a more quantitative comparison). The reference Solar abundances are from Grevesse & Sauval (1998).

For the stellar parameters of the observed stars, first guess values of temperature (T_{eff}) have been derived from optical/IR colors by using the color-temperature transformation of Montegriffo et al. (1998) specifically calibrated on globular cluster giants, gravity (*log g*) from theoretical evolutionary tracks according to the location on the RGB, while for the microturbulent velocity (ξ) an average value of 2.0 km/s has been adopted (see also Origlia et al. 1997).

Abundance analysis is performed by using full spectral synthesis and equivalent width measurements by gaussian fitting the line profiles of representative lines.

$\Delta T_{eff} \mp 200$ K, $\Delta \log g = \mp 0.5$ and $\Delta\xi \pm 0.5$ km s^{-1} variations in the adopted stellar parameters imply a $\leq \pm 0.2$ dex change in the estimated abundances (see ORC02 for more details).

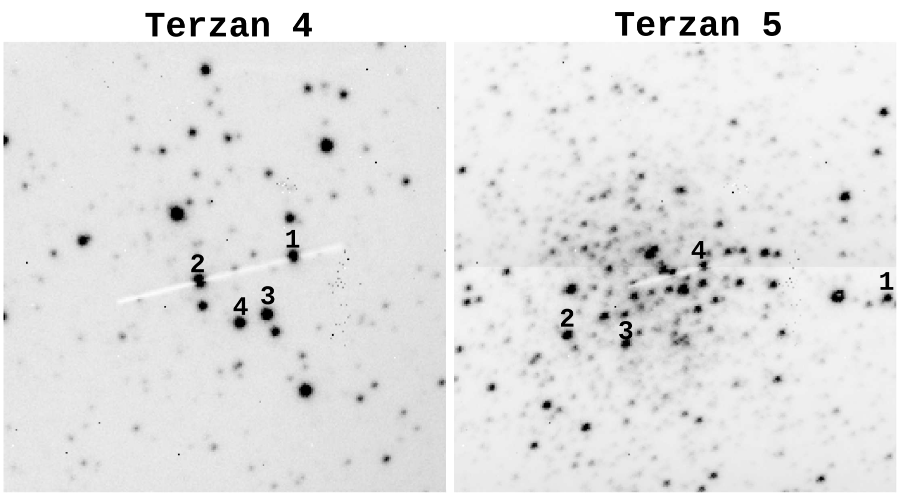

Fig. 1.1. H band images of the core region of the Terzan 4 and Terzan 5 globular clusters taken with the slit viewing camera (SCAM) of NIRSPEC. The observed giants are marked.

However, the simultaneous fit of the different atomic and molecular bands in particular, requires more unique solutions for the adopted stellar parameters, significantly reducing their initial range of variation and ensuring a good self-consistency of the overall spectral synthesis procedure. It is also noteworthy that the stellar features under consideration show a similar trend with variations in the stellar parameters, although with different sensitivities. As a consequence of such a behavior, *relative* abundances are even less dependent on stellar parameter variations.

1.4 Results

By means of full spectrum synthesis and equivalent width measurements of several roto-vibrational OH lines and CO bandheads as well as some atomic lines of Fe I, Mg I, Si I, Ti I and Ca I (see also ORC02) a detailed abundance analysis has been performed on the observed spectra of the globular cluster and Baade's window M–giants.

1.4.1 Globular Clusters

NIRSPEC high resolution H band spectra of 12 giants, members of the NGC 6553, Liller 1, Terzan 4 and Terzan 5 globular clusters, have been analyzed so far. Fig. 1.2 shows the spectra around 1.555 μm of two giants in Terzan 4 and Terzan 5.

Liller 1, Terzan 4 and Terzan 5 suffer of large foreground extinction (E(B–V)$\geq$2), precluding any optical study at high spectral resolution. Recent HST–NICMOS photometry (Ortolani et al. 2001) suggests old ages for these clusters and confirms previous photometric estimates for their metallicities (see Frogel, Kuchinski & Tiede 1995; Ortolani, Barbuy & Bica 1996, 1997; Guarnieri et al. 1998, Davidge 2000): about Solar for Liller 1 and Terzan 5

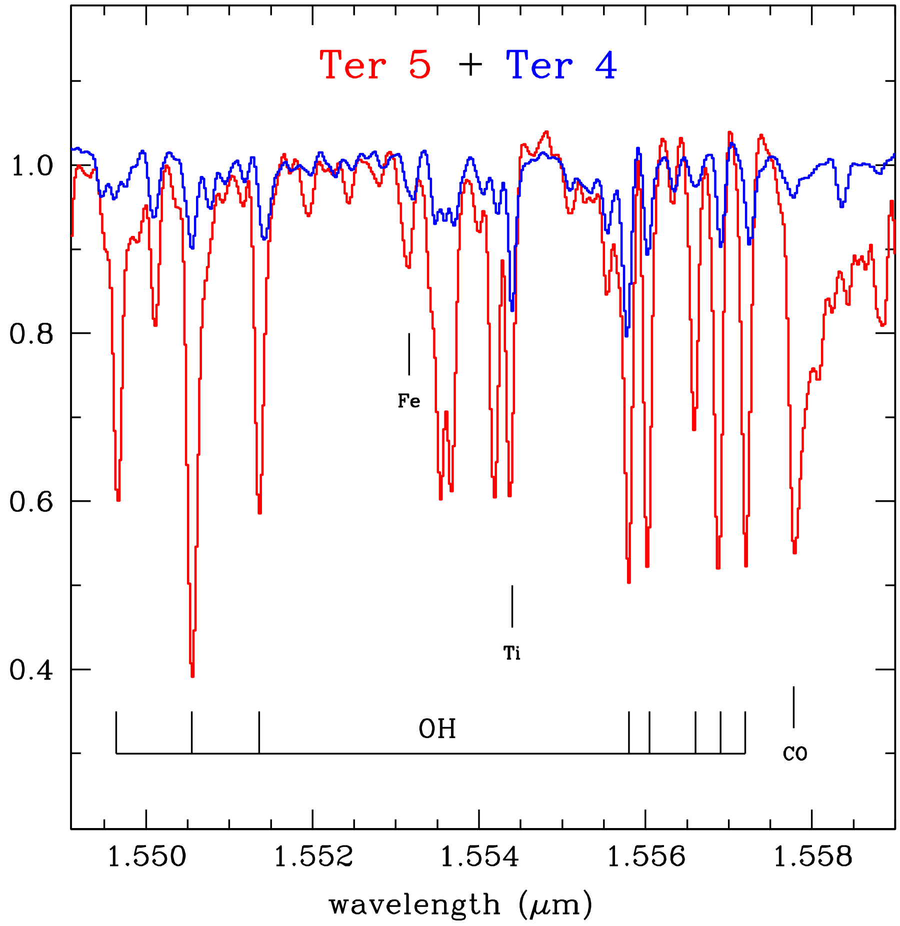

Fig. 1.2. Portion of the NIRSPEC H–band spectrum around 1.555 μm of two giants in the core region of the Terzan 4 and Terzan 5 globular clusters. A few major atomic lines and molecular bands of interest are marked.

and as low as 1/100 solar for Terzan 4. However, accurate abundance measurements from high resolution IR spectroscopy for these clusters were still lacking.

On the contrary, because of the relatively low extinction toward NGC 6553, this cluster has been widely studied in the optical and it is one of the few bulge clusters with a very secure turnoff age measurement. Deep HST imaging finds a main sequence turnoff age coeval with the Galaxy's oldest populations (Ortolani et al. 1995; Zoccali et al. 2001). Despite the relative large number of photometric and spectroscopic measurements in NGC 6553 (cf. e.g. Table 5 of Barbuy et al. 1999 for a summary), the inferred abundances are still somewhat discrepant, leaving open the question of the cluster actual metallicity. In particular the most recent optical studies at high spectral resolution for members of NGC 6553 (cf. e.g. Barbuy et al. 1992; 1999, Cohen et al. 1999) disagree by 0.5 dex.

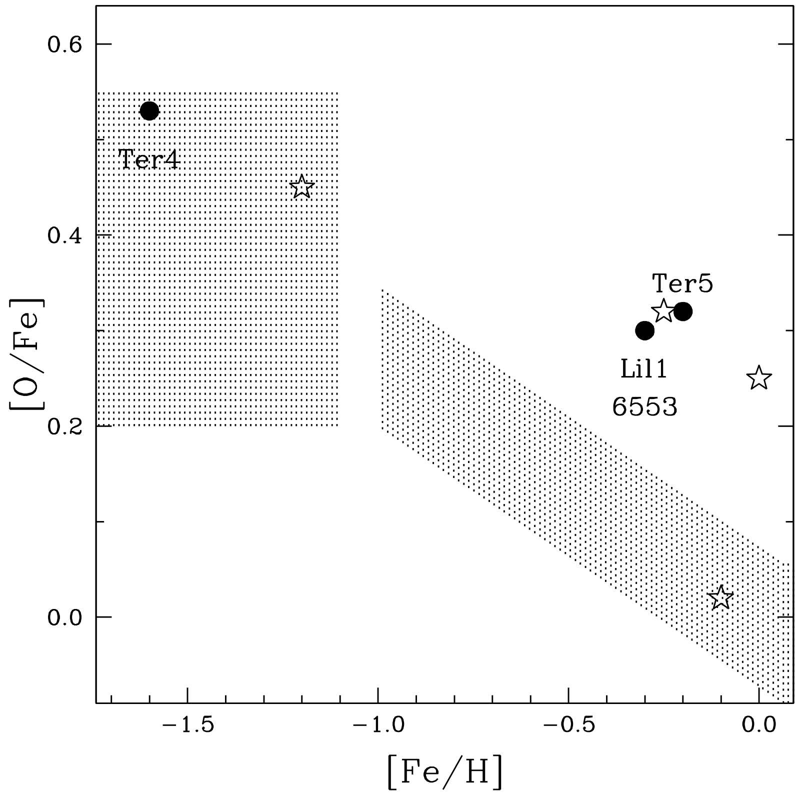

Fig. 1.3. [O/Fe] *vs* [Fe/H] distribution for the Bulge globular clusters in our sample (full dots) and the K–giants in the Baade's window observed by RMW00. The shaded areas represent the average loci of the halo/disk star distribution (from MW97, Fig.3a).

Two bright giants in Liller 1 and NGC 6553 have been observed with NIRSPEC on June 2000, and our abundance analysis is presented in ORC02. We find [Fe/H] = -0.3 ± 0.2 and [O/Fe] = $+0.3 \pm 0.1$ We also measure strong lines for the other α–elements Mg, Ca, and Si, obtaining an overall $[\alpha/\mathrm{Fe}] = +0.3 \pm 0.2$ dex.

Our iron abundance estimate in NGC 6553 is somewhat in between the values proposed by Barbuy et al. (1999) and by Cohen et al. (1999) as revised by Carretta et al. (2001). An overall excess of α-elements by a factor of $\approx$2 is found by all the high resolution studies.

More recently, we have analyzed the spectra of four giants in Terzan 4 and Terzan 5, observed with NIRSPEC on June 2001 and July 2002. We found $[\mathrm{Fe/H}] = -1.6 \pm 0.2$, $[\alpha/\mathrm{Fe}] = +0.5 \pm 0.2$ for Terzan 4 and $[\mathrm{Fe/H}] = -0.2 \pm 0.2$, $[\alpha/\mathrm{Fe}] = +0.3 \pm 0.2$ for Terzan 5. These abundances are fully consistent with the photometric estimates obtained from the cluster RGB morphology (see Ortolani et al. 2001) and confirms the presence of a large metallicity spread in the Bulge as well as in the Halo of our Galaxy.

Fig. 1.3 shows the [O/Fe] trend with [Fe/H] for the globular clusters in our sample. The clusters behave like the K–giants in the Baade's window measured by RMW00 by using the

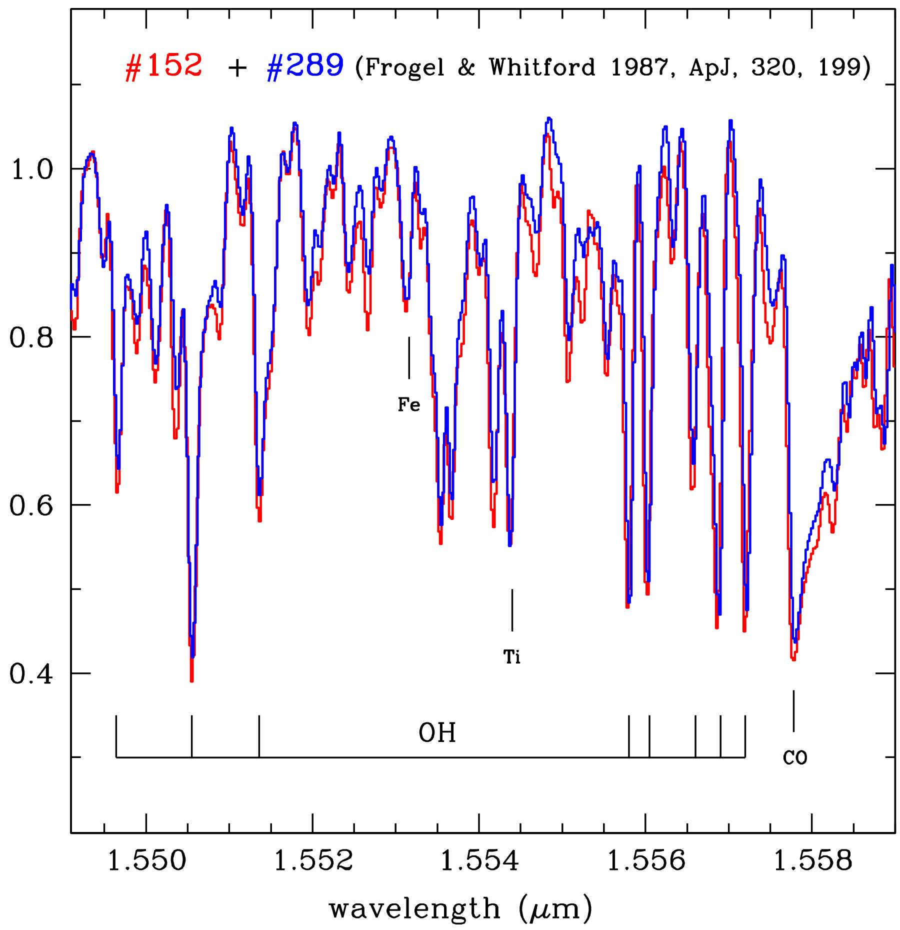

Fig. 1.4. Portion of the NIRSPEC H–band spectrum around 1.555 μm of two M9 giants in the Baade's window. A few major atomic lines and molecular bands of interest are marked.

forbidden [O I] lines to infer the Oxygen abundance. Toward the highest metallicities the disk population show an [O/Fe] about solar, while a significant enhancement is present both in the cluster and in the field population of the Bulge.

A low $^{12}C/^{13}C \leq 10$ isotopic abundance ratio has been measured in all the giants of the four observed clusters, indicating that strong extra-mixing occurred in the stellar interiors during the evolution along the RGB.

1.4.2 M–giants in the Baade's Window

Photometry and low resolution spectroscopy of giant K and M stars in the Baade's window performed in the 1980's (see e.g. Blanco, Blanco & McCarthy 1984; Terndrup 1988, Rich 1988, Terndrup, Frogel & Whitford 1991, Frogel & Whitford 1987) were suggesting an average metallicity [M/H]≈+0.3, considerably in excess of solar, with a larger spread ($\approx$1 dex) among K–giants compared to the one shown by the M–giant population ($\approx$0.3 dex).

The subsequent generations of spectroscopic campaigns in the optical at bigger telescopes and at higher spectral resolution (MWR94; RMW00, McWilliam this conference) provided more detailed abundances of K–giants in the Galactic Bulge. The iron abundance range extends from –1.6 to +0.55 dex, with an average [Fe/H]$\approx$–0.25. α-elements are enhanced even for stars at the solar metallicity. Mg and Ti are enhanced relative to Ca and Si even up to [Fe/H]=+0.55.

M–stars are much more difficult to observe with optical spectroscopy, since their spectra are severely affected by molecular blending and blanketing, while are ideal targets for high resolution IR spectroscopy, made possible by the present generation of IR echelle spectrographs.

NIRSPEC high resolution H band spectra of a sample of M–giants in the Baade's window, with spectral types ranging from M0 to M9 (see Frogel & Whitford 1987) have been obtained on June 2001 and July 2002. Fig. 1.4 shows the spectra around 1.555 μm of the two coolest giants (M9 spectral type) in our sample.

Our preliminary abundance analysis indicates an average [Fe/H]$\approx$-0.2 dex with a small spread ($\approx$0.2 dex) and an overall [α/Fe]$\approx$+0.3 dex enhancement. These abundance patterns are fully consistent with those obtained from the analysis of the K–giant spectra (RMW00, McWilliam this conference).

Similar to what is found for the giants in the globular clusters, a low ^{12}C/^{13}C$\leq$10 isotopic abundance ratio has been also measured in these stars, indicating the presence of extra-mixing processes in their interiors.

1.5 Discussion and Conclusions

High resolution optical/IR spectroscopy is crucial to obtain accurate stellar abundances and abundance patterns in the Galactic Bulge.

Indeed, while low resolution spectra of K and M giants in the Baade's window provided an average metallicity for the dominant stellar population above solar, the subsequent high resolution spectroscopic measurements, much less affected by line blending, lowered the metallicity scale by a factor of $\approx$3. The resulting average metallicity, slightly below solar, is now more similar to the one traced by G and K giants in the solar neighborhood.

The low spread in metallicity shown by the M–giants in the Baade's window compared to the significantly larger one measured among K–giants is not surprising. Only the most metal rich stars become M–giants, reaching temperatures as cool as $\approx$3000 K at the end of their ascent along the RGB.

A small fraction ($\approx$5%) of M–giants with super–solar metallicity should exist, similarly to what observed among K–giants but a much larger sample of stars must be observed in order to detect such a tail (see RMW00) in the metallicity distribution.

Both the globular clusters and field giants analyzed so far, confirms the presence of an overall α–enhancement in the Bulge up to solar metallicity. This suggests a major enrichment of the interstellar medium by type II SNe on timescales shorter than $\approx$1 Gyr, and it is consistent with early and rapid Bulge formation, similarly to the Galactic Halo but possibly at a higher SFR.

This evolutionary scenario for the Galactic Bulge is also supported by a few major theoretical works (see e.g. Matteucci, Romano & Molaro 1999; Wyse 2000, Matteucci this conference).

1.6 Acknowledgments

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