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The Milky Way bulge: stellar abundances and formation in an hierarchical universe

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Abstract. The characteristics of the stars in the Galactic bulge provide important constraints on the overall processes that have been dominant in its formation and that of the Milky Way. This review outlines why, in order to constrain the formation scenarios of the bulge, it is necessary to examine the chemical abundances of stars in the bulge and surrounding disk as a function of other dimensions of information, for example, their kinematics, spatial distribution and ages. Coupling observations to theory is also pivotal in interpreting observational data and for placing constraints on different formation histories.

1. Introduction

The Galactic bulge is a signature of formation of the Milky Way, as different types of bulges are formed via different processes. These different bulge types have unique signatures of formation in their stellar populations. Following Athanassoula (2005), bulges in spiral galaxies can be described within three classes, of

i) classical,
ii) boxy/peanut and
iii) disky or pseudobulges [1].

Classical bulges are large spheroidal bulges with an $r^{1/4}$ light profile and are easily formed in Λ-CDM simulations via hierarchical merging or dissipational collapse. These large bulges are morphologically distinct from the smaller **boxy/peanut bulges**, which have an exponential light profile and are seen to form in simulations from the disk, via dynamical instabilities (i.e Athanassoula 2005; Martinez-Valpuesta et al. 2006; Debattista et al. 2006). In these simulations, a bar forms in the disk, which heats vertically and redistributes stars into the boxy/peanut orbit families (Combes & Sanders 1981; Raha et al. 1991). **Pseudobulges** are central regions of enhanced surface brightness due to ongoing star formation in the plane, as driven by gas inflows to the central region, but do not extend vertically out of the plane like the classical or boxy/peanut bulges. These different bulges have been associated with different signatures of formation in their stellar populations and kinematics. For the stellar kinematics, classical bulges have a slow, spheroidal rotation with slow rotation at high latitudes, whereas boxy/peanut bulges show so called cylindrical rotation, with a similar rotation speed at different latitudes (i.e. Falcón-Barroso et al. 2004). For the stellar population signatures, classical bulges should have experienced a rapid star formation and therefore comprise an old stellar population and a large metallicity gradi-

[1] Boxy/peanut bulges are often termed pseudobulges. We reserve the term psudeobulge for galaxies without a bulge (i.e. extending neither above the disk in a spheroidal nor boxy/peanut morphology).

ent decreasing from the inner to outer extent. Younger stars are expected to be present in boxy/peanut bulges however, due to ongoing star formation in the disk. The Λ-CDM simulations also make an important prediction for classical bulges, that the first generations of stars that were formed, will be found in the inner galaxy (Tumlinson 2010).

Recent simulations demonstrate another route of classical bulge formation via early clump accretion in galactic assembly (Elmegreen et al. 2008). The bulges formed in this method show a characteristic slow rotation and Sersic light profile that is seen in classical bulges formed via mergers or dissipational collapse. Conversely, Inoue & Saitoh (2012) use a higher resolution simulation showing bulge formation via clump accretion and find that the resulting bulge has similar properties to the boxy/peanut bulges of an exponential surface density profile, a barred boxy shape.

2. Examining the Milky Way's bulge

Recent years have seen a shift in the way the Milky Way bulge has been examined in spectroscopic studies, from using small datasets of stars observed at high resolution and concentrated to a few fields (i.e. McWilliam & Rich 1994; Lecureur et al. 2007; Zoccali et al. 2008; Rich et al. 2012), to programs that map across the wider spatial extent of the bulge and out into the disk. The small high resolution surveys have provided important insight into the stellar population in the bulge and with the larger surveys we can characterise the bulge in its full extent and understand this population in relation to the other stellar populations of the Milky Way. Some of these relatively large ground-based surveys are completed (e.g BRAVA Rich et al. 2007, ARGOS Freeman et al. 2013) and others are ongoing (APOGEE Majewski et al. 2007, Gaia-ESO Gilmore et al. 2012 and ESO-large programs, i.e. 4500 stars using FLAMES, PI M. Zoccali). The Gaia satellite mission, launched in Dec 2013 is the most significant paradigm shift to the era of large datasets, obtaining parallaxes, radial velocities and the chemical abundances for the brightest 150 million sources (de Bruijne 2012), including for stars in the bulge. The large photometric surveys of the past decades have provided complementary insights into the stellar population of the bulge (i.e. 2MASS, OGLE, WFI, SOFI, VVV) and have enabled efforts to provide more accurate reddening maps of the bulge (i.e. Gonzalez et al. 2011). This is particularly important near the plane in regions of high differential extinction, where a number of the new spectroscopic surveys will obtain data.

To understand the Galactic bulge, it is important to not only examine the stellar population of the inner galaxy in isolation, but also with respect to the other populations of the Milky Way. To do this, large homogenous datasets which span the inner and outer regions are critical. Stars are tracers of the formation history of the Milky Way because stars that are formed together, will share the same chemical phase-space. Stars that are formed from the same gas cloud should show the same abundance patterns, within which there is a subset of independent markers (Ting et al. 2013). By exploiting this information via so called chemical tagging (Freeman & Bland-Hawthorn 2002), these stars formed from the initial same regions can be identified across large spatial extents. From this it will be possible to test how stars are redistributed in the galaxy, for example from the disk into the bulge, examine the contribution of accretion in the Milky Way bulge and study the role of mergers by using the chemical information and stellar motions to identify streams and debris in the bulge and disk. Using detailed chemical abundances and using models to compare to and interpret the observational data, will be key in the new era of large datasets.

3. The profile of the bulge

The bar-like nature of the Milky Way bulge has been known for some time (Okuda et al. 1977) and the small boxy/peanut profile was revealed by the Two Micron Star Survey (2MASS) star counts (Dwek et al. 1995). The 3D extent of the bulge has recently been mapped in more detail across the inner < 2 kpc using red clump giants, as tracers of the stellar density distribution (Wegg & Gerhard 2013). The type of bulge seen in the Milky Way is not rare, with estimates that around 45% of disk galaxies have a similarly shaped bulge (Lütticke et al. 2004). Therefore, by understanding the Milky Way bulge we are understanding the likely formation processes in disk galaxies in the universe.

The Milky Way's bulge is about 8 kpc away from the Sun (i.e. Gillessen et al. 2009; Wegg & Gerhard 2013) and inclined by about 27° with respect to the line of sight (Wegg & Gerhard 2013, – although estimates vary by about ± 10°). Near infrared star-counts (e.g. López-Corredoira et al. 2005) have indicated the presence of a longer flatter component of the bar that is at a different angle to the barred bulge, although it is argued that this may simply be an artefact of projection and associated with interactions with the spiral features at the end of the shorter bar (Martinez-Valpuesta & Gerhard 2011). N-body simulations predict and observations indicate that boxy peanut bulges are simply parts of bars viewed edge-on (Athanassoula 2005; Bureau & Freeman 1999). The boxy/peanut profile of the Milky Way is consistent with that seen in simulations where a bulge forms from the disk, from the bar that becomes vertically unstable. However, although the boxy/peanut bulge of the Milky Way appears prima facie to be compatible with formation from the disk, different signatures of formation in the stellar population have been interpreted as evidence for a dissipational collapse or merger origin for the bulge.

4. Signatures of formation

4.1. The MDF of the bulge

The stars in the bulge span a wide metallicity range and both high and medium resolution studies find similar metallicity distribution functions (MDFs) for the bulge; with a metallicity range of about –2 to +0.6 dex (Zoccali et al. 2008; Babusiaux et al. 2010; Hill et al. 2011; Gonzalez et al. 2011; Uttenthaler et al. 2012; Johnson et al. 2013; Ness et al. 2013a; Bensby et al. 2013). The high resolution study of about 900 K giants by Zoccali et al. (2008) which examined three fields at the minor axis at b= –4° to b = –12°, first reported the metallicity gradient of the bulge at the minor axis, measuring –0.6dexkpc^{-1} across b= –4° to b = –6°. This metallicity gradient appears to flatten nearer to the plane than $|b|$ < 4° (Ramírez et al. 2000; Rich et al. 2007, 2012). It has been argued that this large metallicity gradient at latitudes $|b|$ > 4° is inconsistent with the scenario where the bulge has formed from the disk via a dynamical instability. The large gradient has been interpreted as evidence that the bulge formed in a rapid burst of star formation at early times, (Zoccali et al. 2008) before the disk. More recent spectroscopic surveys have reinterpreted this gradient, which is now attributed to a composite bulge population and the significantly changing contribution fraction of metal rich stars compared to metal poor stars in the inner galaxy; the fraction of metal rich stars decreases sharply with height from the plane (Babusiaux et al. 2010; Hill et al. 2011; Ness et al. 2013a). Although it was previously believed that dynamical instabilities would not redistribute stars in any preferential way and so any initial disk gradient would be removed, simulations of Martinez-Valpuesta & Gerhard (2013) demonstrate that the initial gradient of the disk is mapped into the bulge in the dynamical instability process. Given a similarly steep initial gradient in the disk, Martinez-Valpuesta & Gerhard (2013) show that the gradient of the Milky Way can not only be reproduced in both the vertical and radial directions, but the metallicity map of the bulge in their simulation shows remarkable similarly to that of Gonzalez et al. (2011) across the inner $|l|$ < 10°, produced from the VVV data. The recent reinterpretation of the metallicity gradients for stars in the bulge and the examination of gradients in the instability simulations, have therefore shown that this large metallicity gradient is consistent with instability formation from the disk.

4.2. Stellar populations in the bulge

Different studies report similar metallicity distributions for the bulge, and this is now believed to comprise a number of populations that change in contribution fraction with height from the plane. Although the bulge is no longer regarded as a single population with a very broad range in [Fe/H], different authors argue for a different number of populations within the MDF, and argue for different origins of formation. Babusiaux et al. (2010) have used vertex deviations of stars in fields near the minor axis, measured as a function of metallicity and Hill et al. (2011) have, via a decomposition of the MDF of these stars, proposed a two-component bulge; a metal rich component that is part of the bar and a metal poor component formed via mergers or dissipational collapse (or a thick disk, see Babusiaux et al. 2010). These two components comprise about 50% each in Baade's window, at $(l, b) \approx (1°,-4°)$, with distributions centred around [Fe/H] ∼ +0.13 and [Fe/H] ∼ –0.31, respectively. From the VVV survey and the photometry of RR Lyrae stars from latitudes < –2.5°, Dékány et al. (2013) have reported that the RR Lyrae population, which sharply peak at an [Fe/H] ≈ –1.0 (Pietrukowicz et al. 2012), does not followed the barred, angled distribution of the more metal rich stars. They suggest that the different spatial distributions of the metal rich and metal poor stars argue for a composite bulge where the metal-poor stars are the classical old spheroidal population. From the ARGOS Galactic bulge survey, Ness et al. (2013a) represent the MDF of the 10,500 stars within R_G< 3.5 kpc across longitudes of $|l|$ ≤ 15° by five Gaussian components. These Gaussian components are fit to the MDF at each latitude, of b = –5°, –7.5° and –10°. These components, represented by A–E from the most metal rich to the most metal poor, change in their contribution fraction with latitude and are shown in Figure 1. Components A-C are the primary components of the MDF in the ARGOS study, comprising 95% of the stars and these Gaussians have a mean value of [Fe/H] of ≈ +0.15, –0.25 and –0.7 dex, with a small gradient decreasing from the plane for these components of < –0.1 dex/kpc. They are proposed in Ness et al. (2013a) to represent (i) A: the metal-rich boxy/peanut bulge with a mean [Fe/H] ≈ +0.15, that is concentrated towards the plane (ii) B: the vertically thicker boxy/peanut bulge contributes a similar fraction of the bulge stars over the latitude range from b = –5° to–10°, (iii) C: the inner thick disc which is at most weakly involved in the boxy/peanut structure of the bulge and which transitions smoothly out into the disk with longitude. The components D and E which represent stars [Fe/H] < –1.0 are tentatively ascribed in Ness et al. (2013a) to the metal-weak thick disc (mean [Fe/H] ≈ –1.2) and stars of the inner Galactic halo.

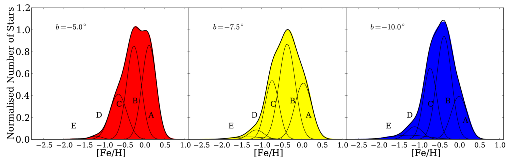

Fig. 1. The metallicity distribution function (MDF) for stars within $R_{\rm Gal}$ < 3.5 kpc. From left to right for stars with $b = -5°$, $b = -7.5°$ and $b = -10°$, for $l = \pm15°$, showing the changing contribution of metallicity fractions with latitude. The five Gaussian components we have identified are indicated (A–E). (Ness et al. 2013b)

4.3. Comparisons to other populations

Comparing stars of the bulge to other populations of the Milky Way, there is evidence for thin and thick disk chemical similarity (Alves-Brito et al. 2010; Bensby et al. 2013; Johnson et al. 2013), although Bensby et al. (2013) find a slightly higher [α/Fe]-[Fe/H] knee of the bulge compared to the thick disk, indicating a faster stars formation rate in the bulge. Barbuy et al. (2013) find chemical similarity for the bulge and thick disk for [Mn/Fe] but not [Mn/O] versus [O/H]. However, their distribution of [Mn/O] appears to track both the thin and thick disk enhancements, which might not be unexpected if the bulge formed from the early disk via dynamical instabilities and stars of the thin disk are present in the inner most region. Surveys that provide coverage of inner and outer regions and which obtain numerous individual elemental abundances (i.e. APOGEE), can be used for comparisons of bulge and disk stars to determine if stars in the inner region at metallicities of the thick disk are in fact thick disk stars (with indistinguishable chemical abundance patterns from the thick disk near the Sun) or else a unique population. i.e. a classical bulge. Similar comparisons can be made between the most metal poor stars of the bulge and stars of the halo. The halo stars are well characterised (i.e. Cayrel et al. 2004; Asplund et al. 2006; Nissen & Schuster 2010) so is is straightforward to compare the most metal poor stars of the bulge region with those of the halo to test if they are likely halo stars in the inner region or comprise part of a classical bulge population.

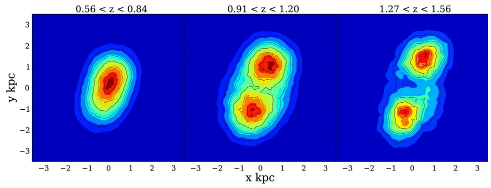

Fig. 2. Contour plots of the (x, y) density distribution of the N-body model in Ness et al. (2012) for three slices in z: $0.56 < z < 0.84$, $0.91 < z < 1.20$ and $1.27 < z < 1.56$ kpc corresponding to the three ARGOS bulge fields on the minor axis of the bulge. The sun lies at y = –8 kpc and the angle between the Sun-Centre line and the major axis of the bar is 20°.

4.4. The X-shape of the bulge

There is a split in the red clump stars along the line of sight near the minor axis at high latitudes from the plane, which is a consequence of its boxy/morphology (McWilliam & Zoccali 2010; Nataf et al. 2010). This has been seen in other galaxies (Patsis & Xilouris 2006; Bureau et al. 2006) and simulations where a boxy/peanut bulge has formed via dynamical instabilities from the disk (Athanassoula 2005; Martinez-Valpuesta et al. 2006; Debattista et al. 2006). Spectroscopic analyses show that not all stars are part of this X-shaped structure and the depth of the split is a function of metallicity (Ness et al. 2012; Uttenthaler et al. 2012). The ARGOS study of the split clump along the minor axis showed that the bimodality is very clear for stars with [Fe/H] > –0.5 in the higher latitude fields along the minor axis (b = –7.5° + b = -10°) and does not appear to be present for the more metal-poor stars with [Fe/H] < –0.5. Using comparisons with an N-body, Ness et al. (2012) and Li & Shen (2012) showed that the split seen at high latitudes is generic to N-body models of boxy/peanut bulges formed via dynamical instabilities. Figure 2 shows three slices across the plane in the inner 3.5 x 3.5 kpc of the model discussed in Ness et al. (2012), showing the density contours of the boxy/peanut-shaped bulge, which produces this X-distribution seen along the line of sight. This dip in stellar density along the line of sight near the minor axis at larger heights from the plane, is a consequence of the orbit families of the stars supporting the triaxial shape (Combes et al. 1990). The metallicity dependence of the split may be due to the preferential redistribution of stars, with the coldest most metal rich stars, that are most closely bound to the plane, extended to the largest distances in the plane, into the X-shape.

4.5. The bulge kinematics

The BRAVA survey (Howard et al. 2008; Kunder et al. 2012) reported cylindrical rotation for the bulge, across latitudes of $|l| < 10°$ and via comparisons with N-body models, Shen et al. (2010) determined that the contribution of any slowly rotating classical component could not exceed 8% of the disk mass. However, the recent work of Saha et al. (2012) showed that any in-place classical bulge will absorb angular momentum from the bar and become a flattened, also cylindrically rotating component, thus removing the kinematic differentiation between a classical and boxy/peanut bulge population. The ARGOS survey expanded on the BRAVA rotation curve, reporting cylindrical rotation out to $|l| < 26°$ from fields observed from $b = -5°$ to $b = -10°$ (Ness et al. 2013b).

The stellar kinematics in the bulge changes with metallicity as reported from a number of studies. For example, from observations in a few select fields, Minniti (1996) found that velocity dispersion increased with decreasing

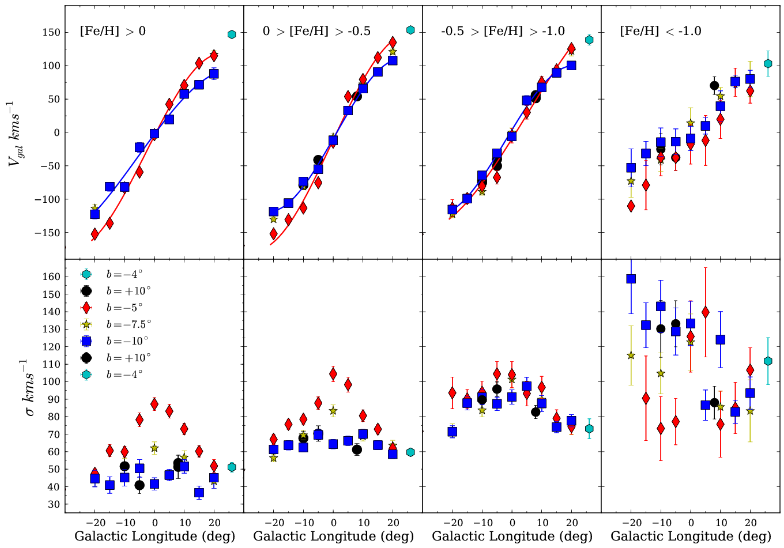

Fig. 3. Rotation curve (top) and Dispersion profile (bottom) for stars in the ARGOS survey within $|y| < 3.5$ kpc of the Galactic centre. Each data point represents the mean velocity and dispersion of the stars in that field. The different panels, from left to right, correspond to the MDF components in Figure 1 of A (3100 stars), B (8700 stars), C (4900 stars) D/E.(900 stars)

[Fe/H] and Babusiaux et al. (2010) measured higher vertex deviations for the metal rich stars. From the larger vertex deviations at high metallicity, Babusiaux et al. (2010) have associated the more metal rich stars with a barred population and the more metal poor stars, with an old spheroid or thick disk. Nearer than $b \geq -4°$ from the plane, there is a change in the [Fe/H]-σ_v relationship and the stars show a higher dispersion at larger values of [Fe/H] (Babusiaux et al. 2010).

From the ARGOS study, the rotation curves and dispersion profile as a function of [Fe/H] demonstrate that all stars with [Fe/H] > –0.5 show a characteristic dispersion profile that is seen in N-body models of instability formation, from the disk, (Shen et al. 2010; Ness et al. 2013b). These are also the stars reported to belong to the split clump in Ness et al. (2012). The metal-rich stars, with [Fe/H] > 0 are a kinematically colder replica of stars –0.5 < [Fe/H] < 0 and stars more metal poor than [Fe/H] < –0.5 show a higher dispersion that is less latitude dependent, compared to the more metal-rich stars. The kinematics of the bulge across [Fe/H] is shown in Figure 3. From this kinematic profile, Ness et al. (2013b) have argued that the stars that are part of the split clump [Fe/H] > –0.5 are consistent with membership of the boxy/peanut bulge and the more metal poor stars, [Fe/H] < –0.5, are likely the thick disk, metal weak thick disk and halo populations, as reflected in the MDF components A-E, from most metal rich to metal poor (Figure 1). There are key signatures in the kinematics of the X-shape and Gardner et al. (2013) have shown that a principal signature is the minimum in the difference between the near and far mean velocity of stars along the minor axis. In the Milky Way, this minimum occurs at $b = -4°$, which is the lower limit of the X-profile.

4.6. Ages of the stars in the bulge

Photometric studies show the stars in the bulge are exclusively old (> 10 Gyrs). These studies report the best fit isochrones to colour magnitude diagrams, for a number of bulge fields (Ortolani et al. 1995; Zoccali et al. 2003; Clarkson et al. 2008; Valenti et al. 2013). The old ages reported for the bulge have been interpreted in favour of the bulge having been formed via an early burst of star formation that is distinct from the formation of the disk. However, this scenario is at odds with the boxy/peanut morphology of the bulge (Wegg & Gerhard 2013). This contradiction has been interpreted by some to support the scenario where by both processes, of dynamical instability and dissipational collapse processes have been important in the formation of the bulge of the Milky Way (i.e. Babusiaux et al. 2010; Hill et al. 2011). Microlensing studies of individual dwarf and sub-giant stars in the bulge within $(|l|, |b|) < (6°,6°)$, have demonstrated that the metal rich stars [Fe/H] > –0.4, show a range in ages (~ 2 - 12 Gyr) whereas the more metal poor stars are all old. This suggests a mixture of populations near the plane and may be related to the change in the line of sight velocity dispersion changes at latitudes $b \geq -4°$, from an increasing dispersion with decreasing [Fe/H] to a higher dispersion at higher metallicities (Babusiaux et al. 2010).

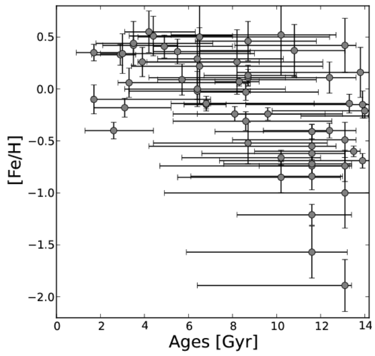

Fig. 4. Stellar Ages versus [Fe/H] for microlensing dwarf and sub-giant stars from (Bensby et al. 2013)

5. Converging on an interpretation

The overall picture of the bulge formation has changed in the last few years. The scenario has shifted from one emphasising mergers or dissipational collapse, as believed to be indicated by the old ages from photometric studies, the high alpha enhancement of the bulge stars and the large metallicity gradient seen along the minor axis, to one where dynamical formation from the disk is considered to play an important role. This shift has been driven by larger data sets, examining more dimensions of information and using models to compare to data and understand the observational signatures.

Although many of the observational results from different studies are similar, there is divergence in the literature regarding the importance of the merger or dissipational collapse scenario in the formation of the bulge. Some analyses propose that mergers or dissipational collapse have played an important role in the formation of the bulge, in addition to the dynamical instability processes. Others suggest that internal dynamical processes have been the primary formation origin of the bulge and any component of a classical bulge, with an origin from mergers or dissipational collapse at early times before the disk, is a relatively minor population.

Two key questions that we need to resolve, in addressing the relative importance of merger or dissipational collapse formation for the bulge are *1) what fraction of stars are not part of the boxy/peanut shape in the Milky Way and 2) what is this population?* The ARGOS study of the split clump argues that stars with [Fe/H] > –0.5 are part of the boxy/peanut bulge formed via dynamical instabilities whereas the stars [Fe/H] < –0.5, which are not part of the split clump, are likely mainly comprised of stars of the thick disk and inner halo. Other studies argue that this more metal-poor population in the inner galaxy is classical bulge, as expected to be present according to Λ CDM simulations. To address the origin of this population, it will be important to exploit the new datasets to examine detailed chemical abundance of bulge stars and compare these to stars of the disk(s) and halo to investigate chemical similarity and dissimilarity at a given [Fe/H]. This will test for the presence of the thick disk and halo in the inner region and using N-body models with star formation for comparison, can be used to study the mapping of the stars from the disk into the bulge in the dynamical instability process, via chemical tagging techniques.

6. Tests of Λ CDM

CDM Simulations predict that the first generations of stars will be concentrated to the bulge region (Diemand et al. 2005; Brook et al. 2007; Tumlinson 2010). Searching for these stars in the bulge is a unique and complementary test of the role that mergers have played in the formation of the Milky Way. Preselected surveys are the only way to target this first generations stellar population and via comparisons with stars of the Galactic halo, the most metal-poor stars in the bulge can be tested for unique chemical markers that would be associated with the first generations of stars (Kobayashi & Nakasato 2011). The SkyMapper telescope (Keller et al. 2007), with its unique metallicity sensitive filter index, is able to identify from a calibrated photometric scale, which stars in a given field in the bulge are the most metal poor candidates for high resolution follow up (see Casey et al. 2012). Finding such a first generations stellar population will and also provide important constraints on the nucleosynthesis of the first stars.

7. Conclusions

Galactic bulges are signatures of formation and it is critical to understand this component of the Milky Way to constrain the formation scenarios of our Galaxy. To understand the bulge, we need to understand the metallicity distribution of stars as a function of other dimensions of information and use models to investigate the observational signatures and their implications. Recent studies have shown that the majority of stars in the bulge belong to the boxy/peanut shape, which is a signature of formation from the disk. However, it is not yet known what fraction of bulge stars are a classical population that has formed in a way that is distinct from the disk, via mergers or dissipational collapse. The metal poor stars of the bulge are not part of the boxy/peanut, but the origin of this population has not yet been definitively demonstrated; it may be a classical bulge or a thick disk (or both). To further understand the bulge and differentiate between these possibilities, it is necessary to make detailed comparisons to models and examine the abundance space of bulge stars and other populations of the Milky Way. This will be possible, using data from the new surveys which provide homogenous coverage over large spatial extents and target new regions in the bulge.

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