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The Stellar Population of the Galactic Bulge

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Abstract. The Galactic bulge is the central spheroid of our Galaxy, containing about one quarter of the total stellar mass of the Milky Way ($\mathrm{M_{bulge}} = 1.8 \times 10^{10} M_\odot$; Sofue, Honma & Omodaka 2009). Being older than the disk, it is the first massive component of the Galaxy to have collapsed into stars. Understanding its structure, and the properties of its stellar population, is therefore of great relevance for galaxy formation models. I will review our current knowledge of the bulge properties, with special emphasis on chemical abundances, recently measured for several hundred stars.

Keywords. Galaxy: bulge, abundances, stellar content, formation

1. The bulge structure

The near infrared images from the COBE/DIRBE experiment clearly showed that our Galaxy has a boxy shaped bulge (Dwek *et al.* 1995). Isophote deprojection revealed a barlike nature, with axes ratios 1:0.33:0.23 and with the near side on the 1^{st} quadrant, at $\sim 20°$ from the Sun-Galactic center direction. These findings were later confirmed by several authors (e.g., Babusiaux & Gilmore 2005; Rattenbury *et al.* 2007a, and references therein), hence the prolate nature of the bulge is now widely accepted. The scale length of the *main* bar is ~ 1.5 kpc. A smaller bar (scale ~ 600 pc) seems to be also present in the inner bulge (Alard 2001, Nishiyama *et al.* 2005), though further studies are needed to confirm and characterize this structure.

A striking feature recently discovered in the outer bulge suggests that the Galactic bulge is all but a simple prolate spheroid. Along the minor axis, at distances in excess of ~ 700 pc, a double red clump is clearly visible in several independent sets of data, symmetric both at positive and negative latitudes (McWilliam & Zoccali 2009). The double clump disappears outside the minor axis, leaving only the brighter of the two at positive longitudes, and the fainter of the two at negative longitudes. Photometric data mapping the whole bulge area are presently available only from the 2MASS survey, which is not faint enough to reach the red clump for $|b| < 3°$. The *Vista Variable in the Via Láctea* survey (Minniti *et al.* 2009) will solve this problem, mapping the whole bulge to much fainter magnitudes ($K_s \sim 20$ in the coadded images), and allowing to deproject its 3D structure by means of its RR Lyrae variable stars.

2. The bulge age

According to galaxy formation models, a bar can be formed through secular evolution of the disk. Dynamical instabilities would cause the bar to buckle (bend), then thicken and eventually look like a *pseudobulge* (Combes & Sanders 1981, Combes *et al.* 1990, Athanassoula & Misiriotis 2002, Athanassoula 2005). Deriving from disk stars, a *pseudobulge* would have several properties, such as kinematics, stellar ages, chemical

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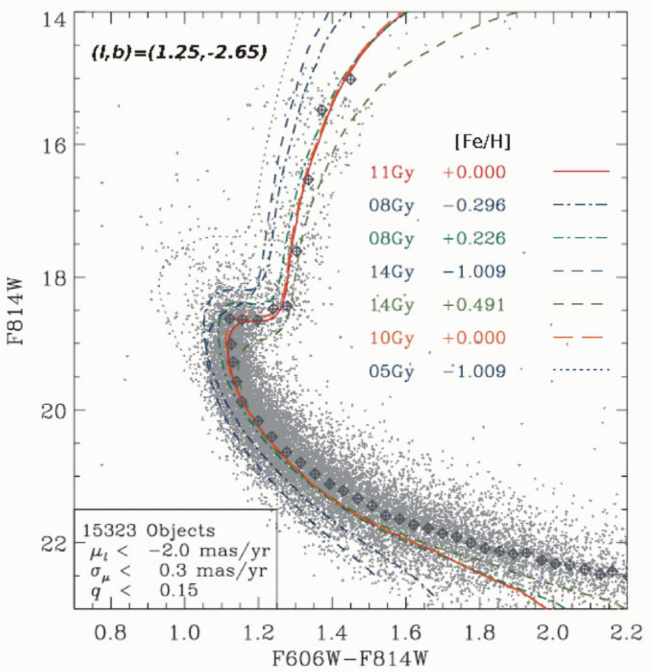

Figure 1. The CMD of a clean sample of bulge stars, selected on the basis of their proper motions. Also shown are isochrones for different ages and metallicities. It is evident that bulge stars follow the old isochrones, with the precise age depending on the adopted metallicity. The residual stars brighter than the old turnoff do not follow a younger isochrone, and indeed Clarkson *et al.* (2009) argues that they are likely to be all blue stragglers. Figure adapted from Clarkson *et al.* (2008).

abundances, resembling more those of galaxy disks rather than those of classical spheroids (Kormendy & Kennicutt 2004).

In contrast with that, Ortolani *et al.* (1995) first demonstrated that the stellar population of the bulge, in Baade's Window at $(l, b) = (0, -4)$, is as old as the stars in the globular cluster 47 Tucanae. This result was later confirmed by Feltzing & Gilmore (2000), Kuijken & Rich (2002), Zoccali *et al.* (2003), and more recently by Clarkson *et al.* (2008) who excluded disk stars from the color magnitude diagram (CMD) on the basis of their proper motions (Fig 1). It should be noted, however, that all the above works studied the bulge stellar population in small fields very close to the minor axis. Dynamical simulation of bulge formation in the bar-driven scenario suggest that the vertical heating is significantly larger at the two ends of the bar, indicating these positions as the places where the intermediate age components should be found (e.g., Debattista *et al.* 2004; and references therein). Due to the larger interstellar extinction, deep photometry reaching the main sequence turnoff away from the minor axis is not yet available in the literature. Some data, acquired with the near IR camera HAWKI@VLT, are under analysis (Valenti *et al.* 2010). Brown *et al.* (2009) present a new photometric system employing five WFC3 bands spanning the UV, optical, and near IR, especially designed to break the degeneracy between reddening, temperature and metallicity, for the forthcoming WF3 Galactic bulge Treasury Program. This program will allow us to derive the bulge star formation history in four fields, including one at the far edge of the bar.

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3. The bulge metallicity

The mean age of the stars, as measured from the magnitude of the main sequence turnoff, is the most direct tool to date the formation of a stellar system. However, the sensitivity of the turnoff magnitude to age decreases for older stellar populations. The difference between two solar metallicity isochrones of 10 and 12 Gyr, respectively, is of $\Delta M_V \approx 0.18$ magnitudes, thus requiring a precision currently impossible to obtain for stars in the bulge, due to the instrinsic spread in distance, metallicity and differential reddening, all concurring to smear out the features of the CMD.

Luckily enough, the chemical composition of the stars has the opposite behaviour. Significant changes in the chemical composition of the interstellar medium, hence on the chemical composition of the newly born stars, occur during the first ~ 1 Gyr from the formation epoch of a stellar system. During that time, indeed, massive stars of different masses explode as core collapse supernovae (SNe), and later on the first thermonuclear SNe start exploding too, all enriching the medium of different kind of elements.

The bulge metallicity distribution function (MDF) was first determined by McWilliam and Rich (1994) who obtained high resolution (R=17,000) spectra of 11 bulge stars, and used them to calibrate a larger (88) sample of low resolution spectra from Rich (1988). They found a broad MDF, peaked at solar metallicity, with a shape roughly compatible with that of a *closed box* model. Mentioning here only works based on high resolution spectroscopy, a new determination of the MDF was made by Fulbright *et al.* (2006) using spectra for 27 stars observed at R$\sim$60,000 to re-calibrate a sample of 217 stars observed at low resolution by Sadler *et al.* (1996). The resulting MDF is very similar, only much smoothed, to the one by McWilliam & Rich (1994). Both these studies were confined to the low extinction Baade's Window. Investigating the presence of a radial metallicity gradient in the bulge obviously requires the observations of many fields, which until a few years ago was only possible through photometry or low resolution spectroscopy. Minniti *et al.* (1995), using both their own and literature data, claimed the presence of a radial gradient, from [Fe/H]$\sim +0.2$ in Baade's Window ($\sim$ 600pc), down to [Fe/H]~ -1 at 2.3 kpc from the Galatic center, along the minor axis. Ramirez *et al.* (2000) and Rich *et al.* (2007a), however, claimed the absence of a gradient from Baade's Window inward. It is worth noticing that the work by Rich *et al.* (2007a) is based on high resolution near IR spectra, for a sample of ~ 15 stars in each of two fields at 140 and 600 pc, respectively.

The advent of the multifibre spectrograph FLAMES allowed a huge step forward in the field. Zoccali *et al.* (2008) acquired GIRAFFE spectra for ~ 700 bulge K giant stars in four different fields, containing 3 globular clusters. Spectra for about 200 red clump stars in Baade's Window, observed through the same setups and conditions, were added to the sample, from the french GIRAFFE GTO programme (Hill *et al.* 2009) The analysis of the stars in the fields along the bulge minor axis allowed to determine the MDF shown in Fig. 2, which is the first one derived from all high resolution spectra (R=20,000). Clearly, the mean metallicity is higher in the innermost field, and decreases towards the outer one. It might also be noted that rather than a solid shift of the MDF towards the metal poor regime, going outwards the metal rich side becomes less and less populated, in favor of the metal poor one, thus suggesting something like a different proportion of populations at different radii. It should be emphasized that all three samples suffer from some degree of contamination from disk stars. The amount of disk contamination, at present, can only be *estimated*, e.g., using the Besançon Galaxy model (Robin *et al.* 2003), resulting in a fraction of 10% in the innermost field, 20% in the intermediate one and up to 50% in the outer one. This percentage, especially in the outer field, cannot be

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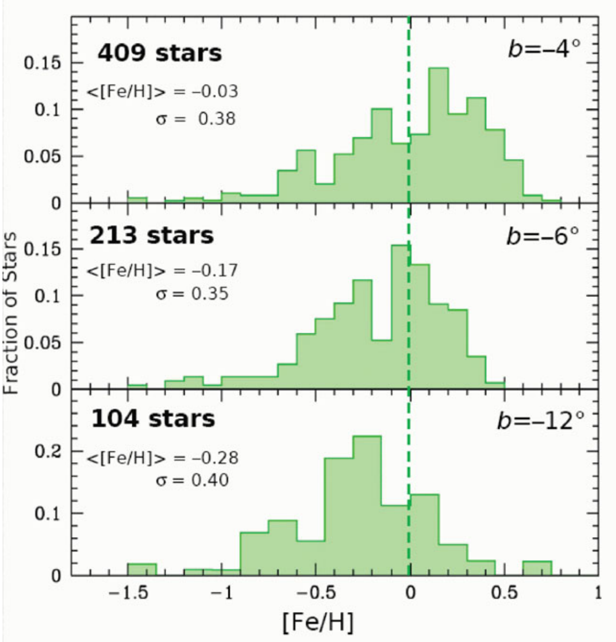

Figure 2. The bulge MDF in three fields along the minor axis, at latitudes listed on the top right corners. Mean metallicities and dispersions are labeled.

neglected and would obviously change the slope of the gradient. However it cannot erase the *presence* of a gradient (see Zoccali *et al.* 2008 for a discussion).

The bulge MDF in Baade's Window obtained by Zoccali *et al.* (2008) is centered at the same mean metallicity than the one by Fulbright *et al.* (2006). However, the former is significantly narrower than the latter, likely due to the smaller errors on the metallicity of individual stars. Recently Rangwala & Williams derived the bulge MDF in a few fields including Baade's Window, by means of Fabry-Perot photometry across the Ca II triplet line at 8542 Å. Their MDF is compatible with both the Fullbright *et al.* (2006) and Zoccali *et al.* (2008) results, once the latter two are convolved with the larger error of the Fabry-Perot measurements.

The presence of a radial metallicity gradient along the bulge minor axis favors a bulge formation through dissipational collapse, against the bar-driven scenario. In fact, the latter is a dynamical process that should not, in principle, segregate metallicities. The independent evidence of the absence of a radial gradient in the inner region ($<$ 600 pc) cannot be contradicted here, thus one should keep in mind the possibility of a two component bulge, uniform in metallicity in its inner part, and with radially decreasing metallicity in the outer part.

Further evidence in the direction of a two component bulge comes from a detailed analysis of the MDF in Baade's Window. The observed MDF, once deconvolved from the estimated errors, appears clearly bimodal (Hill *et al.* 2009). Furthermore, the two components seems to have different kinematics (see below).

It is worth mentioning that in the past few years several high resolution spectroscopic analysis of bulge dwarf stars were carried on during microlensing events that temporarily magnifyied their brightness (Johnson *et al.* 2007, 2008; Cohen *et al.* 2008, 2009; Bensby *et al.* 2009a, 2009b). The results of these analysis were extremely surprising, because the mean [Fe/H] of microlensed dwarfs was too high to be compatible with a random (if

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small) sampling of the bulge MDF obtained from giants. Newer results, however, now including a total of 13 bulge microlensed dwarfs, demonstrate that the initial discrepancy has almost completely disappeared, and it was very likely due to small number statistics (Bensby *et al.* 2009c, these proceedings).

4. Bulge element ratios

Element ratios carry important information about the formation timescale of a stellar system. In particular, the ratio of alpha elements over iron is a measure of the relative contribution of type II SNe (producing mainly alphas) relative to type Ia SNe (producing mainly iron). Therefore stars with $[\alpha/\mathrm{Fe}]$ significantly higher than 0, such as the halo stars, were born before the lower mass type Ia SNe started to explode. McWilliam & Rich (1994) first suggested that bulge stars have alpha element enhancement with respect to the Sun, suggesting a rapid star formation for the bulge. Rich & Origlia (2005) confirmed this result with near IR spectra, though only for stars in a narrow range of $-0.35 <[\mathrm{Fe/H}]< 0$. Zoccali *et al.* (2006) and Lecureur *et al.* (2007) extended the former studies to a sample of 50 stars, observed with UVES (R=45,000) simultaneously to the GIRAFFE observations mentioned above, and spanning $-0.8 <[\mathrm{Fe/H}]< +0.4$. Their results confirmed the alpha element enhancement of bulge stars, well reproduced by chemical evolution models assuming a rapid (~ 1 Gyr) star formation timescale (Immeli *et al.* 2004; Ballero *et al.* 2007).

Lecureur *et al.* (2007) found that different elements, such as oxygen and magnesium, behave differently, when plotted against [Fe/H], thus supporting theoretical models with metallicity dependent stellar yields (c.f., McWilliam *et al.* 2008; Cescutti *et al.* 2009).

By comparing the $[\alpha/\mathrm{Fe}]$ trend of bulge K giant stars with that of solar neighborhood dwarfs (Bensby *et al.* 2004; Reddy *et al.* 2006) Zoccali *et al.* (2006) and Lecureur *et al.* (2007) concluded that the bulge is chemically different from the (local) thin and thick disks, and it must have formed more rapidly than both of them. These findings were confirmed by Cunha & Smith (2006), Fulbright *et al.* (2007) and Rich *et al.* (2007a). More recently, Meléndez *et al.* (2008) questioned the above conclusions. By means of a homogeneous comparison of new near IR spectra of bulge K giants with similar data for thin and thick disk K giants, they found a similarity in the [O/Fe] abundances of bulge and thick disk stars, supporting a similar origin -or at least formation timescale- for both components.

The origin of the different result of Meléndez *et al.* (2008) is the systematically higher [O/Fe] they found for both thin and thick disk giants, while the bulge abundance ratios are consistent with all the previous results. They correctly emphasize the importance of a homogeneus comparison between the same kind of stars (K giants) in the bulge, thin and thick disk. Some of the previous studies (Fulbright *et al.* 2007; Rich *et al.* 2005, 2007a) also included spectra for disk K giants, analysed in the same way as the bulge ones, and yet yielded lower [O/Fe] than bulge stars. However, the separation between thick and thin disk stars for this purposes must be done on the basis of kinematics only, it is very tricky, and it has not been discussed extensively in the papers mentioned above. Further investigation is needed in order to clarify whether the bulge and the thick disk do share the same element ratios, thus might have similar origin (e.g., Alves Brito *et al.* 2009, these proceedings).

The new, high resolution (R=70,000) near IR spectrograph CRIRES@VLT allowed Ryde *et al.* (2009) to obtain precise measurements of C,N,O elements in a sample of bulge K giants all included in the FLAMES-UVES sample observed by Lecureur *et al.* (2007). Their [O/Fe] for bulge stars are compatible with most previous measurements,

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but have smaller statistical errors. The comparison with the thick disk giants observed by Meléndez *et al.* (2008) confirmed the chemical similarity between the two components.

It might be worth mentioning that high resolution near IR spectra have recently been obtained for a sample of red supergiant in the Galactic center (< 50 pc). All the available studies (Cunha *et al.* 2007; Davies *et al.* 2009; Najarro *et al.* 2009) agree on a [Fe/H] distribution sharply peaked around ~ 0.1; and on [O/Fe] ratios evenly spread between $+0.05$ and $+0.45$. The reason for alpha element enhancement in this case is rather unclear. The independent evidence of intense star formation in this region (e.g., An *et al.* 2009) implies recent formation of massive stars – thus core collapse SNe shortly after – naturally enriching the inter stellar medium of oxygen and other alphas. Alternatively – or simultaneously – it might also be that the recent star forming activity in the center was fueled by gas coming from the bulge/bar (known to produce gas inflows), hence already enriched by different kind of SNe and stellar winds, explaining the unusual element ratios.

5. The bulge kinematics

Several bulge proper motions studies have been carried on in different bulge windows, mostly for bright stars. Only in a few cases the photometry was deep enough to allow the kinematical decontamination of the turnoff region of the CMD (Zoccali *et al.* 2001; Kuijken & Rich 2002; Clarkson *et al.* 2008). Other studies aimed at the characterization of the bulge rotation and velocity dispersion, in order to understand if the bulge exibits a solid body rotation, if there are streaming motions, asymmetries, and if there is any evidence of different sub-populations with different kinematics (Spaenhauer *et al.* 1992; Alcock *et al.* 2001; Sumi *et al.* 2004; Rattenbury *et al.* 2007a,b; Vieira *et al.* 2007; Soto, Kuijken & Rich 2007). Vieira *et al.* (2007, their Table 2) give a compilation of the available determinations of proper motions dispersions, all compatible within the errors with their $\sigma(\mu_l) cosb = 3.39 \pm 0.11$ mas/yr and $\sigma(\mu_b) = 2.91 \pm 0.09$ mas/yr.

Stellar kinematics can help understanding the nature of the Galactic bulge. In fact, it is expected that a *pseudobulges* formed through secular evolution of the disk will have a larger rotation compared to classical ones, and the rotation velocity is expected to be constant with galactic latitude. In the so-called Binney (1978) diagram, showing the ratio of the maximum rotation velocity over velocity dispersion, versus the asymmetry parameter, *pseudobulges* are expected to lie above classical ones. The galactic bulge, with its $V_{\rm max}/\sigma \sim 0.65$ (Rich *et al.* 2007b; Minniti & Zoccali 2007) is consistent with classical spheroids in external galaxies. However, the latest results of the BRAVA survey (Howard *et al.* 2009) demonstrated that the rotation velocity of the bulge is constant with latitude (cilyndrical rotation), as expected for *pseudobulges* and opposed to a rotation velocity decreasing outwards, typical of classical spheroids (Combes *et al.* 1990; Fux 1997, 1999; Zhao *et al.* 1996; Athanassoula & Misiriotis 2002; Athanassoula 2005)

Once more, the nature of the Galactic bulge seems consistent with either a classical or a *pseudo* bulge, depending on the tools used to probe it. A possible solution comes from the evidence that the metal rich and metal poor component have different kinematics, the first one more typical of a bar-like structure, the second of a dynamically hot system (Soto *et al.* 2007; Babusiaux *et al.* 2009).

6. Conclusions

The nature of the Galactic bulge is somehow puzzling. Its stellar population is old ($10 - 12$ Gyr) and it has a metallicity distribution compatible with chemical enrichment

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models assuming a fast star formation. The abundance ratio of alpha elements over iron also supports a short star formation timescale, certainly more rapid than that of the thin disk, and possibly more rapid than that of the thick disk. The presence of a radial metallicity gradient, at least outside ∼600 pc, favors a formation scenario via dissipational collapse, rather than secular evolution of the disk. Nevertheless, the bulge has the shape of a bar (perhaps including some X-shape feature in the outer part) and a cylindrical rotation velocity, both characteristics of a *pseudobulge* formed via dynamical heating of a bar, resulting from disk secular evolution.

A possible solution to these conflicting results may come from the confirmation of a double component bulge, as already suggested by several studies (e.g., Soto *et al.* 2007, Hill *et al.* 2009, Babusiaux *et al.* 2009) and seen in several bulges of external galaxies (Peletier *et al.* 2007).

In any case, it is now clear from several independent evidences that the Galactic bulge is a complex structure. There is a metallicity gradient in the outer region that seems not to be present in the inner region. There are indications that the MDF in Baade's Window is bimodal, with each of the two component having different kinematics. Stellar ages are predicted to be different along the minor axis, compared to the edges of the bar. Even the morphology itself does not seem to be simply that of a bar, but rather something like an X-shape. The properties of the stellar population in Baade's Window cannot be considered as representative of the whole bulge: larger area photometric and spectroscopic *maps* are needed in order to understand the bulge structure and origin. The VVV survey, and its spectroscopic followups, will certainly reserve many surprises in this sense.

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