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# FORMATION AND EVOLUTION OF THE GALACTIC BULGE

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RESUMEN

A pesar de su importancia como el único esferoide galáctico totalmente resuelto en estrellas, nuestro conocimiento del bulbo Galáctico ha sido historicamente bastante pobre. Eso se debía principalmente a la dificultad en resolver estrellas en regiones tan densas, a la importante absorción interestelar en el plano Galáctico, y a la contaminación por estrellas pertenecientes al disco. Sin embargo, en los ultimos años, con el uso de los detectores infrarrojos, junto a los telescopios de 8 metros (o bien espaciales), y a la disponibilidad de espectrógrafos multi-objeto, hemos logrado reducir al mínimo los efectos mencionados arriba. En este artículo se examinan las propiedades básicas (parámetros estructurales, edad, abundancias químicas) del bulbo Galáctico, a la luz de los descubrimientos de los ultimos 4–5 años.

ABSTRACT

Despite its importance as the only galactic spheroid fully resolved in stars, our knowledge of the Galactic bulge has been historically quite poor. This was mainly due to the stellar crowding, to the heavy interstellar absorption in the plane, and to the foreground disk contamination. However, in the last few years, with the use of near IR detectors, 8 meter class (or space based) telescopes, and the advent of multi-object spectrographs, we have learnt how to minimize the above effects. This paper reviews the basic properties (structural parameters, age, chemical content) of the Galactic bulge, as determined in the last 4–5 years.

*Key Words:* Galaxy: bulge — Galaxy: formation — Galaxy: stellar content — stars: abundances



## 1. INTRODUCTION

The *bulge* is the spheroidal component at the center of the Milky Way. Its total mass is about $1.6 \times 10^{10}$ $M_\odot$ (Popowski et al. 2005; Hamadache et al. 2006; Sumi et al. 2006), about 4 times smaller than that of the disk ($7 \times 10^{10}$ $M_\odot$), and 16 times larger than that of the halo ($\sim 10^9$ $M_\odot$). These numbers are useful to have in mind because if we want to understand the formation our Galaxy, we should try and understand the formation of disk and bulge, contaning most of the mass, with the halo contributing only a few percent to the Galaxy total stellar mass. On the other hand, while the disk is currently forming stars, the bulge seems to have passively evolved for the last $\sim$ 10 Gyr (see below), hence it is the ideal fossil probe of the Galaxy formation.

Beside the obvious morphological similarity, there are several quantitative indications that the stellar population of spiral bulges resembles that of elliptical galaxies. For instance, they follow the same Fundamental Plane relation (Falcon-Barroso et al. 2002) and the same mass metallicity relation (Jablonka et al. 1996). For these reasons, it is common to refer to spiral bulges and elliptical galaxies with a unique word: galactic *spheroids* (Renzini 2006). Galactic spheroids are known to host the majority of the stellar mass of the Universe ($\sim$ 70%; Fukugita, Hogan, & Peebles (1998), hence understanding their formation mechanism is crucial to understand the history of the mass assembly of the whole Universe. In this context, the Galactic bulge is very special, being the *only* spheroid that can be resoved into individual stars down to the bottom of the main sequence. It is also the only one for which detailed chemical abundances can be derived from high resolution spectroscopy (i.e., from resolved atomic lines as opposed to line indices).

This picture, however, has been challenged by Kormendy & Kennicutt (2004), who noted that "*some bulges are really disks*". Some *pseudo*-bulges, as they called them, are in fact flatter than classical bulges, often peanut or boxy shaped, they have higher rotation velocity to velocity dispersion ratios, they contain younger stars, show spiral structures and bars, and have nearly exponential light profiles. Pseudo-bulges are believed to be the result of the secular evolution of disks, via the formation of a bar, whose buckling instability would produce vertical heating, thus generate a peanut (pseudo) bulge. Kormendy & Kennicutt also argue that "*because latest-type galaxies are (pseudo) bulgeless, secular evolution is likely to be most important in intermediate-*

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*late type galaxies (Sbc)".* The Milky Way is indeed a Sbc Galaxy, hence it is important to establish whether its bulge is a prototypical spheroid (formed at early times, just like any elliptical galaxies) or it is a thickened bar, slowly created by the disk secular evolution.

## 2. THE BULGE 3-D STRUCTURE AND KINEMATICS

The near IR images of the Milky Way Galaxy from COBE (Dwek et al. 1995) clearly show that, projected in the plane of the sky, the bulge appears peanut shaped. Several surveys have recently provided important clues on the bulge 3-D structures, namely: the MACHO survey (e.g., Popowski et al. 2005) and the OGLE I and II survey (e.g., Rattenbury et al. 2007). Both of them were looking for stellar variability and microlensing events, but as a side result, the analysis of the red clump magnitude (a known distance indicator) across the surveyed area allowed to determine the bulge 3D structure. It was then established that the Galactic bulge is in fact a bar, with axis ratio of 1:0.35:0.26 and the major axis lying in the plane of the Milky Way, inclined by 25° toward positive longitudes with respect to the $l = 0°$ direction. These numbers are quoted from the latest analysis, by Rattenbury et al. (2007) , but other authors have found compatible results (see Gerhard 2002 for a review).

The 3-D structure of the bulge would then suggest a pseudo-bulge nature. We also know that the bulge is rotating, with a peak rotation of about 75 km/s (Minniti et al. 1992; Harding & Morrison 1993; Minniti 1996; Ibata & Gilmore 1995; Beaulieu et al. 2000; Rich et al. 2007a) and it has a rather large velocity dispersion, decreasing towards the Galactic center (Terndrup et al. 1995; Minniti et al. 1995; Ibata & Gilmore 1995). However, the $V_{\rm max}/\sigma$ plot shown in Figure 1 (Binney 1978; adapted by Kormendy & Kennicutt 2004) demonstrates that the Galactic bulge, with $V_{\rm max}/\sigma = 0.67$, is not peculiar with respect to classical bulges, not showing evidences of an especially high rotation velocity (Minniti & Zoccali 2007).

## 3. THE AGE OF THE BULGE

Obviously, in order to understand the bulge formation history a crucial piece of information comes from the age of its stars. Using the luminosity function, Ortolani et al. (1995) measured the magnitude difference between the horizontal branch and the turnoff, a known age indicator, of bulge stars. A comparison of this difference in the bulge with that

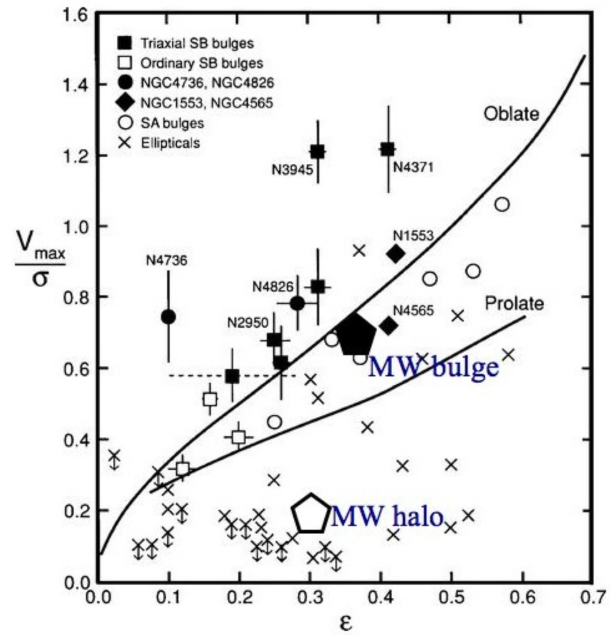


Fig. 1. Milky Way bulge and halo position in the Binney (1978) diagram adapted from Minniti (1996) and Kormendy & Kennicutt (2004).

of metal rich globular clusters revealed no age difference between the two, hence an old age for the bulk of bulge stars. Zoccali et al. (2003) made a similar measurement, this time based on a near IR color magnitude diagram statistically decontaminated from foreground disk stars. The result was the same, an old (∼ 10 Gyr) age for the bulk of bulge stars, with no trace of intermediate or young population.

The main limitation of these works comes still from the foreground disk contamination. A statistical decontamination with a disk control field has been possible, but it is not the ideal solution because it assumes uniformity between the disk along different line of sights. The desirable approach would be a star by star decontamination, i.e., a procedure able to tell exactly which (turnoff) star belongs to the bulge and which one does not. In principle this is possible via kinematical decontamination, for example using stellar proper motions, as shown by Kuijken & Rich (2002). Recently, the deepest color magnitude diagram (CMD) available so far for the bulge (Figure 2) has been obtained with HST+ACS within a project devoted to the search of planets in the Galactic bulge (Sahu et al. 2006). Second epoch data allowed to obtain proper motions for this field (Clarkson et al. 2008) isolating a *bona fide* pure bulge population. Due to the large overlap between

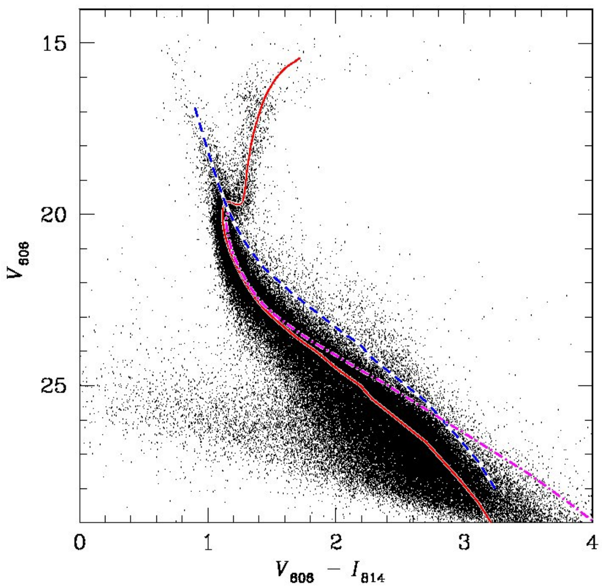


Fig. 2. The deepest bulge CMD from $\sim 90,000$ sec exposures in both the F606W (V) and F814W (I) bands, obtained with the ACS@HST on a $202'' \times 202''$ field at $l, b = 1.6, -3.2$ (Sahu et al. 2006). About 245,000 stars are plotted down to $V = 29$. A Solar metallicity isochrone of 10 Gyr is shown as a red solid line, fitting the bulk of the bulge population. The foreground disk is fit with an unevolved main sequence shown by the blue dashed line. A super metal-rich isochrone with $[Fe/H] = +0.5$ is also shown with the magenta dot-dashed line.

the proper motion distribution of disk and bulge stars, however, this procedure requires the selection of the tail of the bulge proper motion distribution, hence reducing dramatically the number of stars.

The fact that the great majority of bulge stars are old is clearly seen from Figure 2 and it is now firmly established. Current uncertainties concern: (*i*) the possible presence of a *trace* population of intermediate age stars, expected (if present) to lie preferentially at the edges of the bar rather than along the minor axis, where most of the deep photometric studies have concentrated; and (*ii*) the possible existence of an age spread. While certainly present, the latter is very hard to quantify at the moment, at least from photometry, because several other factors concur in causing a magnitude spread at the turnoff, namely: distance spread, differential reddening and a rather wide metallicity distribution.

## 4. THE BULGE CHEMICAL CONTENT

One way to overcome the limitations of the age determination is to measure detailed chemical abundance of bulge stars. Those represent the fossil record of the chemical composition of the interstellar medium at the epoch of formation of each measured star. Knowing the place and mechanism of formation of the different elements, we are able to identify which source (SNII, SNIa, AGB winds) had enriched the medium previous to the star formation, and from its lifetime we can infer the time of the formation of that star.

### 4.1. *Metallicity Distribution Function*

The metallicity distribution function (MDF), e.g., the histogram of iron content, provides important clues on whether the bulge evolved as an isolated system, or it adquired (infall) or expelled (outflow) gas from/to other galactic components.

Starting with the spectroscopic study of Rich (1988), the distribution function of the iron abundance among bulge stars has been further explored and refined by McWilliam & Rich (1994), Minniti (1996), Sadler et al. (1996), Ramirez et al. (2000), and Fulbright et al. (2006), using spectroscopic observations, and by Zoccali et al. (2003) with a purely photometric method. Among them, the McWilliam & Rich (1994) and Fulbright et al. (2006) analysis deserve special mention because they were the only ones to obtain high resolution spectra for a small sample of stars, used to calibrate some previous, low resolution analysis for a larger sample. All mentioned spectroscopic surveys were carried on using long-slit spectrographs, thus observing just one or two stars at a time. With the advent of the FLAMES multiobject spectroscograph at the VLT (Pasquini et al. 2003) it then became possible to observe a large number of objects simultaneously.

The first MDF obtained from high resolution spectroscopic analysis of each individual star is the one of Zoccali et al. (2008), based on a sample of $\sim 400$ stars in Baade's Window (at $b = -4°$), $\sim 200$ stars in a Blanco field at $b = -6°$ and $\sim 100$ stars in a Blanco field at $b = -12°$. Figure 3 compares their MDF in Baade's Window with the previous result by Fulbright et al. (2006). The MDF by Zoccali et al. (2008) is narrower than previously found. This would be consistent with the hypothesis that the new results have a smaller error, as it should be. However, Figure 3 also shows as a solid histogram the 27 stars that were actually measured by Fulbright et al. (2006) at high spectroscopic resolution. Those are the stars that were used to recalibrate the Sadler et al. (1996) MDF obtained from low resolution spectra. It can be appreciated that none of the 27 stars has [Fe/H]$> +0.5$, despite their selection of 3 stars with [Fe/H]$\geq +0.5$ in Sadler et al. (1996). The discrepancy at the metal rich end is in a region were

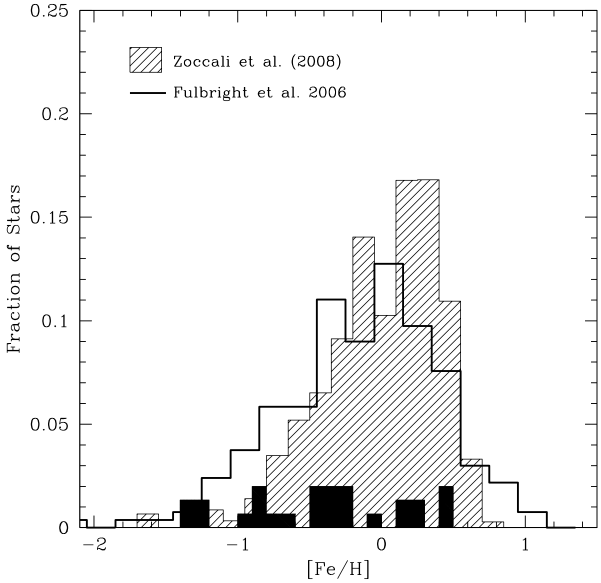


Fig. 3. The spectroscopic MDF by Fulbright et al. (2006) in Baade's Window is compared with the Zoccali et al. (2008) results. Also shown as a black solid histogram (arbitrarily normalized) is the MDF of the 27 stars actually observed by Fulbright et al. (2006) at high spectral resolution.

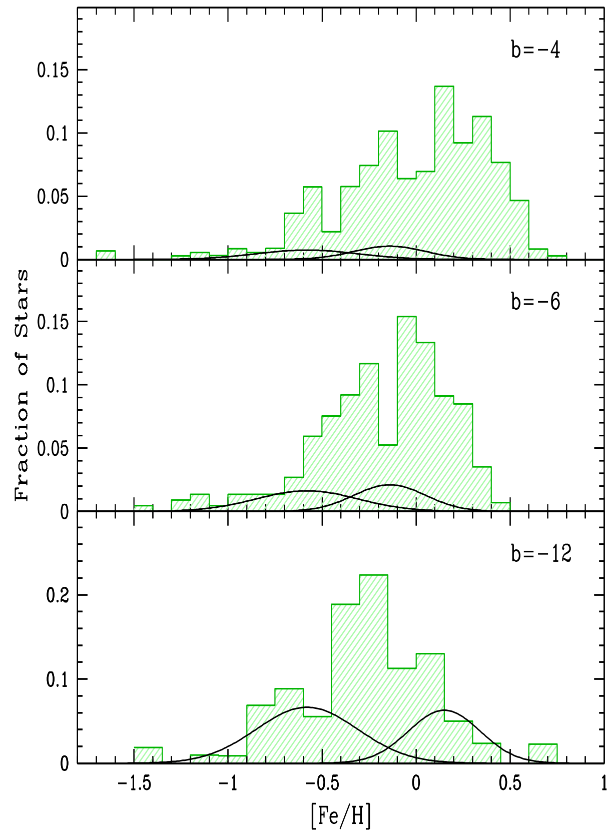


Fig. 4. The latest bulge MDF from Zoccali et al. (2008) in three fields along the bulge minor axis, from the innermost one (Baade's Window, top) to the outermost one (bottom). The gaussians show the MDF of contaminating thick and thin disk stars, normalized to the expected contamination fraction, according to the Besançon Galaxy model.

the Fulbright et al. calibration was in fact used in extrapolation. In addition, the strong Mg2 features found in the most metal-rich and cooler stars are contaminated by TiO Lines (see, e.g., Figure 13 by Coelho et al. 2005) and the Sadler et al. (1996) MDF itself probably has an overestimated high metallicity tail. Less obvious is the interpretation of the discrepancy at low [Fe/H] with respect to the MDF by Fulbright et al. (2006).

The data by Zoccali et al. (2008) also reveal the presence of a radial metallicity gradient along the bulge minor axis, as shown in Figure 4. Overplotted to the metallicity distribution of bulge stars (histograms) are two gaussians qualitatively showing the estimated contamination by thick and thin disk. The gaussians have indeed the mean and sigma values characteristics of the thick (Reddy et al. 2006) and thin disk MDF (Nordström et al. 2004), in the solar neighboorhood. After subtracting the estimated contamination fraction, the bulge MDF has a mean value dropping from $<[\mathrm{Fe/H}]>=+0.03$ at $b=-4^\circ$ to $<[\mathrm{Fe/H}]>=-0.12$ at $b=-6^\circ$, and to $<[\mathrm{Fe/H}]>=-0.27$ at $b=-12^\circ$. While the result in the outermost region is highly uncertain due to the large disk contamination, the comparison between the two inner fields clearly indicates the presence of a gradient. It is interesting to note that in the past, different teams have found contradictory results about this (e.g., Terndrup et al. 1995; Minniti et al. 1995; Ramirez et al. 2000). More recently Rich et al. (2007b) do not find any difference between the mean metallicity of a field at $b=-1^\circ$ and Baade's Window at $b=-4^\circ$. One possibility to explain the discrepancy between the latter work and the gradient shown in Figure 4 might be that the metallicity gradient is not present *inside* a radius of 600 pc from the Galactic center, corresponding to $b=-4^\circ$. The presence of the gradient has quite strong implications with respect to the bulge formation, being the signature of a fast dissipative collapse, as opposed to dissipationless stellar merging. The proposed scenario of the bulge resulting from vertical heating of an instable bar would also produce a uniform bulge, without gradient, since dynamical effects are obviously blind to chemical content.

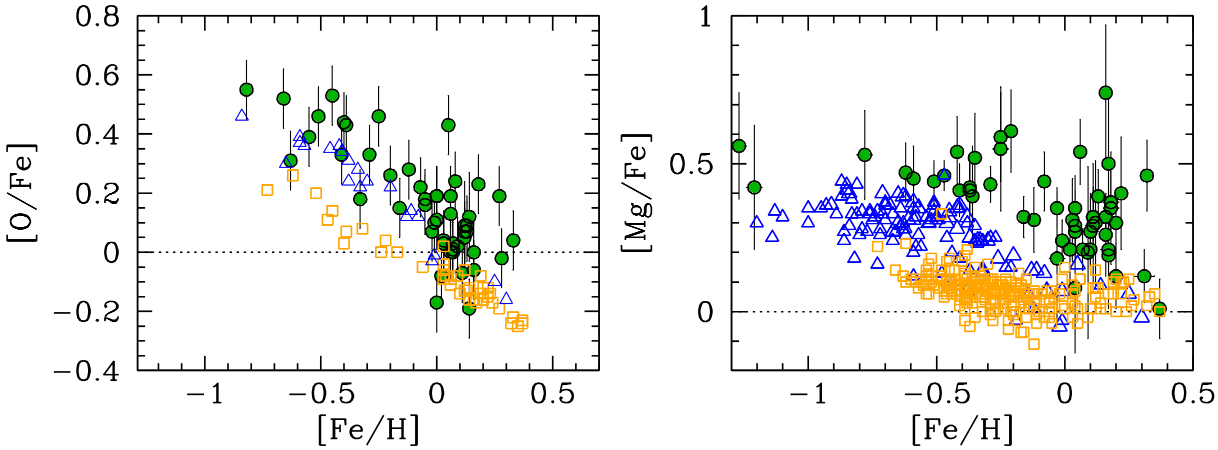


Fig. 5. Oxygen and magnesium over iron ratios as measured from high dispersion spectra of bulge K giants (Zoccali et al. 2006; Lecureur et al. 2007). Green circles with error bars are bulge stars, compared with thick (blue triangles) and thin (red squares) disk stars. These results clearly indicate that the bulge formed as a separate component by a rapid chemical enrichment.



### 4.2. *Alpha Element Abundance*

Different teams were pursuing the detailed element abundances of bulge giants using high dispersion spectrographs, following the pioneering effort by McWilliam & Rich (1994). Recently, Rich & Origlia (2005) and Rich et al. (2007) found that alpha elements are enhanced to [O/Fe]=+0.4 for $\sim$ 30 giants (in two fields) within a narrow metallicity range around [Fe/H]=−0.2. Later on, Zoccali et al. (2006) and Lecureur et al. (2007) measured oxygen, magnesium, sodium and aluminum in a sample of 50 K giants with [Fe/H] from −0.8 to +0.3 using the UVES spectrograph at the VLT. The result is shown in Figure 5, where it is evident that bulge stars have larger [O/Fe] and [Mg/Fe] than both thin and thick disk stars. These results agree with the previous ones by Rich & Origlia, and were later confirmed by independent teams: Fulbright et al. (2007) analyzed 27 K giants, and Cunha & Smith (2006) observed 7 giants, all with enhanced oxygen with respect to the other Galactic components, at all metallicities.

The alpha element enhancement is the signature of a chemical enrichment by massive stars, progenitors of SNII, with little or no contribution from lower mass, SNIa, and thus of a shorter formation timescale of the bulge with respect of both disk components. In this sense, the bulge (including its globular clusters) is the most extreme Galactic population.

## 5. SUMMARY

Based on the empirical evidences presented above, it can be concluded that the bulge is indeed a distinct Galactic component, with different kinematics and composition from the disk(s) and the halo. The bulk of its stellar population is $\sim$ 10 Gyr old. Traces of intermediate age stars might be present away from the minor axis, where most deep CMDs have been obtained. The bulge must have formed on a short timescale ($\sim$ 1 Gyr) as demonstrated by the alpha element abundances. Despite the presence of the bar, a bulge formation via secular evolution of the disk can be firmly excluded due to the chemical differences between bulge and disk, and to the presence of a radial metallicity gradient in the bulge. We note that the bulge chemical composition is also different from that of stars belonging to nearby dwarf spheoidals (Venn et al. 2004; Monaco et al. 2007) thus excluding accretion from satellites like the surviving ones in the Local Group.

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