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A review of the chemical abundances and kinematics of the Galactic bulge

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Abstract. This review will attempt to draw a *state of the art* observational picture of the Galactic bulge. The main chemical, kinematic and evolutionary properties of the gas and stellar populations in the barred bulge and towards the Galactic center region will be discussed in the context of the possible formation scenarios. Future perspectives for our comprehension of the complex structure of the Galactic bulge from ongoing and foreseen optical and infrared surveys will be also highlighted.

Keywords. Galaxy:bulge, abundances, kinematics and dynamics, stellar content, structure

1. Introduction

The central region of our Galaxy shows several sub-structures, namely an inner thin disk, a bulge, a denser inner bulge, a bar structure within the inner bulge, also referred as the peanut-shaped bar/bulge and the Galactic center region. The latter is also a complex system with a central molecular zone, including a ring and a nuclear disk, and a nuclear bulge (e.g. Launhardt, Zylka & Mezger 2002). The bulge as a whole accounts for about 25% of the bolometric luminosity and 20% of the mass of the Milky Way. Any precise definition of the bulge extension is somewhat arbitrary. In the following I will call inner bulge the densest region within approximately the central kpc, and the outer bulge the region out to 3 kpc in radius from the Galactic center.

The inner Galaxy in general, and the bulge in particular is thus a complex puzzle. The first complication comes from severe obscuration along the line of sight. A major responsible for such an extinction is a molecular ring located at about 5 kpc from the Galactic center and 3 kpc from us (e.g. Clemens, Sanders & Scoville 1988, Sodroski *et al.* 1997). This dust screen is rather extended and with a patchy distribution, blocking most of the optical radiation from the inner Galaxy and limiting our view through a few, preferential holes, only. This is the reason why infrared and radio observations are so crucial to explore the inner Galaxy. It is also interesting to recall that the molecular ring has a mass of 2×10^9 $M_\odot$ and it contains about 70% of the molecular gas inside the Solar Circle (e.g. Combes 1991, Dame, Hartmann & Thaddeus 2001, Misiriotis *et al.* 2006).

In this review I will touch a few major topics namely *i*) the patchy extinction toward the Galaxy central region, *ii*) the several sub-structures of the inner Galaxy and of the bulge in particular, *iii*) the age, chemistry and kinematics of their stellar populations, *iv*) some open/controversial issues, and finally *v*) today and future spectroscopic surveys of the bulge and innermost regions of the Galaxy.

More extensive presentation and discussion of the properties of the Galactic bulge can be found in Rich (2013).

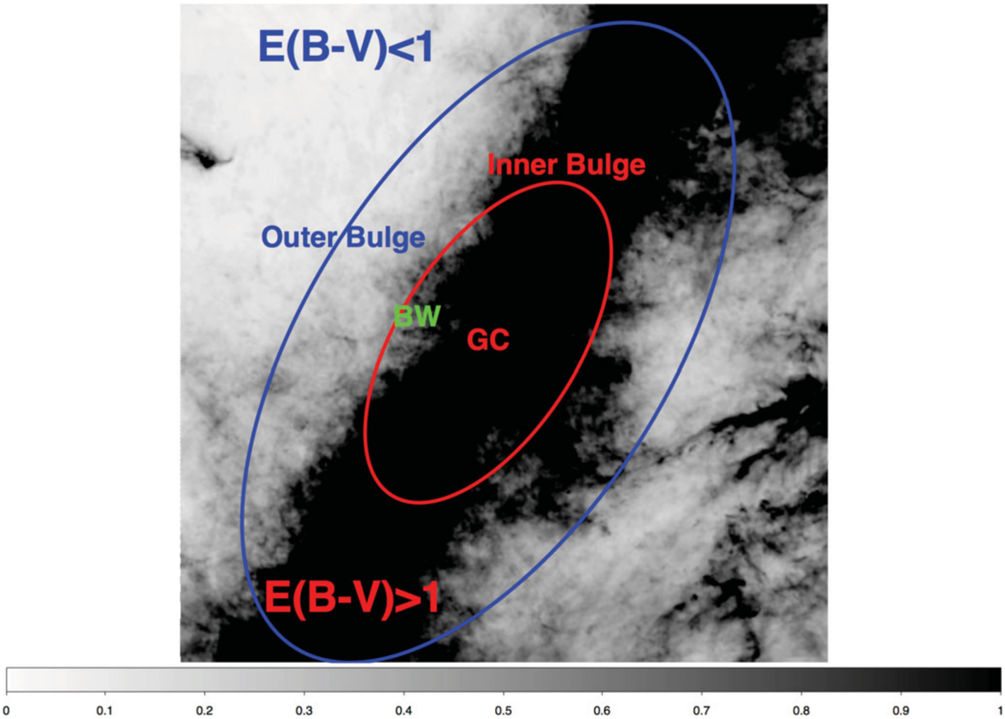

Figure 1. $E(B-V)$ reddening map of the central part of the Galaxy, with sketched the outer (3×1.5 kpc) and inner bulge (1.5×0.75 kpc) regions. The positions of the Galactic centre (GC) and Baade's window (BW) are indicated. North is down, East is left.

2. The patchy extinction towards the Galactic bulge

Fig. 1 shows an E(B-V) reddening map (Schlegel, Finkbeiner & Davis 1998) of the central part of the Galaxy. The white to gray regions are those with low to moderate reddening, i.e. E(B-V)<1 and still somewhat observable at optical wavelengths, while the dark regions suffer of high extinction and they are observable at infrared wavelengths, only. This is especially the case for the inner bulge and disk, with the only exception of Baade's window and of the SWEEPS/Sgr1 field at l=1.25^o and b=-2.65^o, and it is also the case for a significant fraction of the outer bulge.

It is interesting to note that, because of the huge extinction and the lack of efficient infrared spectrographs at medium-high resolution with multi-object capabilities, the large majority of chemical and kinematic information on the inner bulge still come from optical surveys in Baade's window, only, hence, our vision and comprehension of the central bulge is far from being exhaustive.

New and more detailed extinction maps for the bulge, based on the VISTA-VVV and 2MASS surveys, (Gonzalez *et al.* 2012 and references therein) have been recently made available to the community.

Also the inner disk is poorly explored due to the large extinction. Most measurements in the inner disk are still at a minimum distance of about 4 kpc from the Galactic center (see e.g. Andrievsky *et al.* 2013, Genovali *et al.* 2013, and references therein, for recent chemical abundance determinations in Cepheids) and indicate the existence of a positive metallicity gradient towards the inner regions and metal abundances well in excess of Solar.

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In the innermost disk region and in the Galactic center only measurements of some supergiants exist so far (e.g. Ramirez *et al.* 2000a, Martins *et al.* 2008, Najarro *et al.* 2009, Davies *et al.* 2009a, Davies *et al.* 2009b), consistent with metal abundance around Solar and some level of alpha-element enhancement (e.g. Cunha *et al.* 2007).

3. Bulge sub-structures

The actual structure of the bulge, a triaxial, oblate system with a central, massive bar (e.g. Rich 1990, Dwek *et al.* 1995, Robin *et al.* 2005) as well as its actual surface brightness profile, a power-law typical of massive bulges or by an exponential-law typical of small bulges in late type galaxies, are matter of discussion since many years.

The presence of a massive bar has been the topic of extensive debate over the years and different observables have been used to trace it, namely *i*) kinematics of HI gas (Liszt & Burton 1980) and planetary nebulae (Beaulieu *et al.* 2000), *ii*) asymmetries in surface brightness and red clump distributions from COBE/DIRBE/2MASS (Babusiaux & Gilmore 2005) and more recently from the VVV-VISTA (Gonzalez *et al.* 2011b) surveys, *iii*) optical depth gradients from microlensing experiments (see Hamadache *et al.* 2006 and references therein, see also Zhao, Rich & Spergel 1996, Alcock *et al.* 1998, Bissantz & Gerhard 2002).

Recently, another piece of evidence for the presence of a bar came from the discovery of a double red clump and an X-shaped bulge (e.g. McWilliam & Zoccali 2010, Nataf *et al.* 2010, Saito *et al.* 2011, Ness *et al.* 2012, Vasquez *et al.* 2013), that turns out to be mostly a distance effect and explained as the bar viewed tangentially, while it appears boxy/peanut-shaped when viewed from the Sun.

The main bar structure has a length of 3 kpc, a $\approx 0^o$ pitch angle, an inclination angle between 15^o and 30^o, depending on the tracer, and axial ratios of 1.0:0.3:0.3 (e.g. Freudenreich 1998, Bissantz & Gerhard 2002, Evans & Belokurov 2002, Soto, Kuijken & Rich 2012). Recently, new OGLE-III data suggest an inclination angle between 29^o and 32^o and axial ratios of 1.0:0.41:0.38 (Cao *et al.* 2013).

Other bar sub-structures have been claimed over the years, although still somewhat debated (see e.g. Gerhard & Martinez-Valpuesta 2012), in particular *i*) an inner bar, hundreds of parsec long and with a steep inclination angle of 70^o, from 2MASS (Alard 2001) and from CO observations (Sawada *et al.* 2004); *ii*) a longer, flatter structure (8x1.2x0.2 kpc) with an inclination angle of 43^o from 2MASS (Lopez-Corredoira *et al.* 2007, Cabrera-Lavers *et al.* 2007).

4. Bulge stellar populations

In order to characterize the bulge properties and constrain the possible scenarios for its formation and evolution, it is of primary importance to analyze its stellar content and in particular to answer three fundamental questions about their stellar populations: 1) How old are they? 2) What is their detailed chemical composition? 3) What is their kinematics and their most suited membership to possible spheroid, bar or disk components?

4.1. *Bulge age*

Once properly decontaminated by field stars through statistical and especially proper motion analysis, the color-magnitude diagrams of Baade's window and the SWEEPS/SGR1 field in the inner bulge from HST photometry (e.g. Kuijken & Rich 2002, Sahu *et al.* 2006, Clarkson *et al.* 2011), as well as of the outer bulge from near infrared ground based

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photometry (e.g. Zocccali *et al.* 2003) show main sequence turnoff populations consistent with ages older than 10 Gyr and with no major evidence for a younger component.

Very similar conclusions have been obtained by analyzing the turnoff region in the color-magnitude diagrams of globular clusters, by using both HST optical photometry (e.g. Ortolani *et al.* 1995, Heasley *et al.* 2000, Ortolani *et al.* 2001, Zoccali *et al.* 2001) and ground based adaptive optics near infrared photometry (e.g. Origlia *et al.* 2008). Bulge globular clusters are old, similarly to 47 Tuc and other disk/halo metal rich clusters.

Further significant evidence for the old age for the bulge stellar populations comes from the presence of RR Lyrae stars both in the field (e.g. Alcock *et al.* 1998, Collinge, Sumi & Fabrycky 2006) and in globular clusters (e.g. Layden *et al.* 1999, Pritzl *et al.* 2002, Clementini *et al.* 2005).

Although there is a general consensus that the bulk of the bulge stellar population is old, there is also some evidence for the presence of an intermediate-age population. This includes OH-IR and Mira variables (e.g. Sjouwerman *et al.* 1998, Blommaert & Groenewegen 2007, C-stars (e.g. Cole & Weinberg 2002 but not confirmed by Ojha *et al.* 2007), and more recently young dwarfs from microlensing experiments (e.g. Bensby *et al.* 2013 and references therein), their precise age depending, however, on the He content adopted for the isochrones (see Nataf & Gould 2012 for a more exhaustive discussion). Young and intermediate-age stellar populations are definitely present in the central 100 pc (e.g. Mezger *et al.* 1999, Blum *et al.* 2003, van Loon *et al.* 2003, Figer *et al.* 2004, Schuller *et al.* 2006).

4.2. *Bulge chemical abundances*

The study of the Galactic bulge by means of medium-high resolution spectroscopy started less than two decades ago, taking advantage of the few existing optical and infrared echelle spectrographs.

After the pioneering work by McWilliam & Rich 1994, who first measured a sample of K giants in Baade's window at medium spectral resolution and for the first time found evidence for alpha-element enhancement in metal rich stars, a few other medium-high resolution surveys in the same field by observing either K giants in the optical (Zoccali *et al.* 2003, Zoccali *et al.* 2006, Fulbright, McWilliam & Rich 2007) and M giants in the near infrared (Rich & Origlia 2005), have been undertaken in the 2000's.

All these surveys confirmed the presence of alpha-element enhancement at least up to Solar metallicity.

However, only in the recent years, taking advantage of the new generation of optical multi-object spectrographs like UVES-FLAMES at the VLT and Hydra at the CTIO, more systematic and massive surveys of Baade's window and of a few other fields in the outer bulge at Galactic longitudes around 0^o and latitudes from -4^o out to -12^o have been made possible (e.g. Zoccali *et al.* 2008, Alves-Brito *et al.* 2010, Gonzalez *et al.* 2001a, Hill *et al.* 2011, Johnson *et al.* 2011, Uttenthaler *et al.* 2012). Some other off-axis fields have been also recently surveyed by Johnson *et al.* 2013.

The central 500 pc of the inner bulge, because of the huge extinction, have been solely surveyed in the near infrared using NIRSPEC at KeckII (Rich, Origlia & Valenti 2007, Rich, Origlia & Valenti 2012).

It is interesting to note that when using faint giants/red clump stars to trace the metallicity distribution, the latter appears somewhat bimodal, with peaks at sub-Solar and super-Solar [Fe/H], the precise values also depending on the field location, while when using bright giants the distribution appears moderately broad, with a more single peak at [Fe/H] between about one third and Solar, also depending on the field location and in particular on its Galactic latitude.

Notably, the bright giant populations show a deficit of stars with super-Solar [Fe/H] when compared to the corresponding faint giant/red clump ones (see Rich, Origlia & Valenti 2012, Uttenthaler *et al.* 2012 for a more exhaustive discussion).

Despite some uncertainties on the exact shape of the metallicity distribution, these recent surveys confirmed the previous claim of a vertical abundance gradient in the outer bulge (e.g. Minniti *et al.* 1995, Frogel, Tiede & Kuchinski 1999), although somewhat less steep (recent results from the VVV-VISTA survey suggest 0.04 dex/deg, Gonzalez *et al.* 2013). Such a gradient disappears/flattens in the innermost 500-700 pc (Ramirez *et al.* 2000b, Rich, Origlia & Valenti 2012).

Concerning the [α/Fe] abundance ratio, all bulge fields show a very similar trend, with enhancement up to about Solar [Fe/H], and then a progressive decline towards Solar values at super-Solar [Fe/H]. This trend is at variance with either the one observed in the thick disk, where the knee occurs at significantly lower [Fe/H] and with the rather flat distribution of the thin disc with Solar [α/Fe].

Measurements of light element (e.g. Na, Al) as well as heavy r and s-process element abundance ratios (Johnson *et al.* 2012, see also Fulbright, McWilliam & Rich 2007) indicate that the bulge population is quite distinct from the thick disk and the most metal poor component also behaves differently from the halo. Notably, [Eu/Fe] follows the trend of the [α/Fe] abundance ratios, indicating that at least the stars with [Fe/H]$\leqslant$0 should have formed from a gas mainly enriched by type II SNe on short timescales.

The measurement of chemical abundances in dwarf stars from microlensing experiments (e.g. Bensby *et al.* 2013, see also Cohen *et al.* 2010) also suggest the presence of two populations, a sub-Solar and old one with alpha enhancement, and a younger, more metal rich one with decreasing alpha enhancement with increasing [Fe/H], the position of the knee being at [Fe/H]$\approx$–0.2, that is at somewhat higher metallicity than the corresponding knee of the thick disk distribution.

Finally, chemical abundances have been also measured in bulge/inner disk planetary nebulae (e.g. Gutenkunst *et al.* 2008, Gorny *et al.* 2009, Chiappini *et al.* 2009, Guzman-Ramirez *et al.* 2011), indicating a systematically lower metal content than in stars and a plateau in the radial distribution within the innermost 3 kpc, quite distinct from the gradient measured in the outer disk (see also e.g. Stanghellini & Haywood 2010).

4.3. *Bulge kinematics*

In the recent years, two major radial velocity surveys of the outer bulge have been undertaken, by exploiting the multi-object capabilities of optical spectrographs at 4-8m class telescopes.

The Bulge RAdial Velocity Assay (BRAVA, Rich *et al.* 2007, Howard *et al.* 2008, Howard *et al.* 2009, Kunder *et al.* 2012) exploiting Hydra at the CTIO measured 4,500 M giants in different fields at Galactic longitudes between -10^o and $+10^o$ and Galactic latitudes between -4^o and -8^o. The BRAVA survey provided the first observational evidence for cylindrical rotation in the Galactic bulge, typical of boxy structures (e.g. Shen *et al.* 2010, Saha & Gerhard 2013). The observed radial velocity and velocity dispersion distributions are well modeled by a single massive bar, with no evidence for a classical bulge or cold streams.

The Abundances and Radial velocity Galactic Origins Survey (ARGOS, Freeman *et al.* 2013, Ness *et al.* 2013a, Ness *et al.* 2013b) exploiting AAOmega, measured 28,000 stars in the bulge and inner disc. The ARGOS survey found evidence for two main distinct populations with a rotating bar kinematics: a sub-Solar component with alpha enhancement and a metal rich one (with a peak at [Fe/H]$\approx$+0.15), which is a somewhat slower rotator and it is kinematically colder than the metal-poorer one, and it is also less alpha enhanced. A minor (5%) metal-poor [Fe/H]<-1.0) population, with kinematics typical of a slowly rotating spheroidal or a metal weak thick disk component, has been also inferred.

A few other high resolution spectroscopic surveys of the outer bulge at Galactic latitudes between -4^o and -12^o mostly with UVES-FLAMES at the VLT (e.g. Babusiaux *et al.* 2010, Uttenthaler *et al.* 2012) and with Hydra at the CTIO (Johnson *et al.* 2011) provided simultaneous chemical and radial velocity measurements for reasonably large samples of bulge giants and red clump stars.

In all surveys, for a given Galactic latitude, there is a general trend of decreasing velocity dispersion with increasing metallicity, with the only exception of the measurements by Babusiaux *et al.* 2010 in Baade's window, who found the highest velocity dispersion being at the super-Solar metallicity. Notably, Ness *et al.* 2013b in their close field at $b=-5^o$ did not confirm such a high velocity dispersion at super-Solar metallicity.

The same surveys also indicate that at [Fe/H]<–1.0 the velocity dispersion remains about constant around 100 km/s regardless the Galactic latitude, typical of spheroids, while at [Fe/H]>–1.0 it decreases with increasing latitudes, suggesting the presence of a bar which is somewhat denser closer to the plane.

5. Bulge stellar systems

Fundamental information on the bulge stellar populations are also provided by its globular clusters and other more complex systems like Terzan 5 is (see e.g. Valenti, Ferraro & Origlia 2007).

The bulge globular cluster system spans almost two orders of magnitudes in iron abundance, between about 1/100 and Solar (e.g. Harris 1996), and its metallicity distribution is shifted towards lower metallicities when compared with the field. Because of the huge extinction in the direction of the majority of bulge globular clusters, only a few of them can be spectroscopically observed in the optical (see e.g. Carretta *et al.* 2001, Gratton *et al.* 2006, Gratton *et al.* 2007, Barbuy *et al.* 2009 and references therein).

So far, the largest spectroscopic survey of cool giants in bulge globular clusters has been undertaken in the near infrared, using NIRSPEC at KeckII over the last decade (Origlia, Valenti & Rich 2008, Valenti, Origlia & Rich 2011 and references therein). Bulge globular clusters show α-enhancement at a level of a factor between 2 and 3 over the whole range of metallicity, without any evidence for vertical abundance and other abundance pattern gradients, suggesting an early and rapid formation.

As a whole, the globular cluster system has kinematics consistent with a spheroidal component, although less luminous objects show somewhat lower velocity dispersions, more consistent with a bar or a disk system (e.g. Burkert & Smith 1997). Detailed proper motion analysis of a few bulge globular clusters (Dinescu *et al.* 2003, see also Ortolani *et al.* 2011) suggest that their velocity confined them in the bulge region, but the metal poor clusters have kinematics more consistent with a halo/thick disk component, while the metal rich ones have kinematics consistent with either bulge, bar or thin disk components.

5.1. *The puzzling case of Terzan 5*

Terzan 5 is a stellar system in the inner bulge of the Galaxy that has been classified as a globular cluster for years, although soon after its discovery its true nature was already disputed (see e.g. King 1972). More recently, by means of high resolution imaging in the near infrared obtained with the Multi-conjugate Adaptive Optics Demonstrator (MAD)

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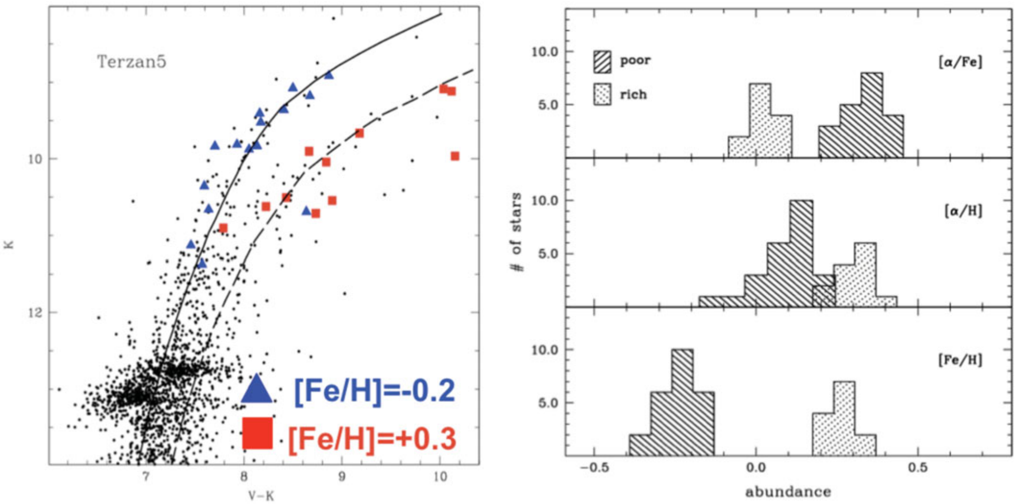

Figure 2. K, (V-K) color-magnitude diagram (left panel) of Terzan 5 (Ferraro *et al.* 2009) corrected for differential reddening (Massari *et al.* 2012), with highlighted the stars for which detailed abundances have been measured (Origlia *et al.* 2011). The corresponding histograms of the [Fe/H], [α/H] and [α/Fe] distributions are reported in the right panel.

at ESO-VLT, it has been revealed the presence of two distinct red clumps that cannot be explained by differential reddening or distance effects (Ferraro *et al.* 2009).

Prompt near infrared spectroscopy with NIRSPEC at KeckII demonstrated that the two stellar populations are characterized by very different iron abundances ([Fe/H]= ?0.2 and +0.3). Subsequent spectroscopic studies (Origlia *et al.* 2011) fully confirmed the large metallicity difference between the two sub-populations, also revealing a small metallicity spread within each of them, distinct [α/Fe] abundance patterns and no evidence for the Al-Mg and Al-O anti-correlations commonly observed in globular clusters.

In particular, as shown in Fig. 2, the metal-poor population is alpha-enhanced and closely resembles the bulk of the old bulge population, which formed early and quickly from a gas mainly polluted by a huge amount of type II SNe. The metal-rich population, which is possibly a few Gyr younger, has an approximately Solar [α/Fe] ratio, requiring a progenitor gas polluted by both type II and type I SNe on a longer timescale. Terzan 5 was therefore able to retain the SN ejecta and give rise to two distinct populations with different iron content and alpha enhancement, but small metallicity spread within each of them. This evidence and the higher central concentration of the most metal-rich component could be explained within a self-enrichment scenario, where the proto-Terzan 5 was possibly much more massive in the past than today (its current mass being 10^6 $M_\odot$, Lanzoni *et al.* 2010), and two main and relatively short episodes of star formation have occurred with a few Gyr delay.

The expected high number of type II SNe would have also produced a large population of neutron stars, most of which would have been retained within the deep potential well of the system. Then the high collision rate of Terzan 5 (the highest among all globular clusters, Lanzoni *et al.* 2010) could have favored the formation of binary systems containing neutron stars and promoted the recycling process that finally generated the huge population of millisecond pulsars (MSPs) now observed in Terzan 5 (this is indeed the largest MSP population ever detected in any stellar system, e.g. Ransom *et al.* 2005).

The striking chemical similarity between Terzan 5 and the bulge population suggests a strong evolutionary link between these two stellar systems and possibly a common origin

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and evolution. Moreover, at least the bulge population of microlensed dwarfs appears to show an abundance/age dichotomy similar to that of Terzan 5.

Hence, Terzan 5 might well be the relic of a larger sub-structure that lost most of its stars to the bulge, probably because of strong dynamical interactions with other similar systems at the early epoch of the Galaxy formation, and/or later on with the central disk/bar. While most of the early fragments dissolved/merged together to form the bulge, for some (still unclear) reasons Terzan 5 survived the total disruption (Ferraro *et al.* 2009).

Note that, within this scenario Terzan 5 would be an invaluable probe of the bulge history, its most metal-poor population tracing the early stages of the bulge formation process, and its most metal-rich one containing crucial information on its more recent chemical and dynamical evolution.

6. Bulge formation and evolution: open issues and future prospects

The current observational picture for the bulge formation and evolution is still rather controversial. Both the old age and chemical abundances indicate an early and rapid formation, from a gas mainly enriched by type II SNe on a short timescale. The only possible exception are the most metal rich (super-Solar) stars, which may be younger and have formed from a gas also enriched by type I SNe on longer timescales.

Stellar kinematics is consistent with a massive, metal rich bar-like structure, typical of pseudo-bulges and possibly a metal-poor spheroidal component.

The canonical formation picture is that spheroidals form via early mergers (e.g. Immeli *et al.* 2004, Carollo *et al.* 2007, Elmegreen, Bournaud & Elmegreen 2008), and/or dissipative collapse (e.g. Ballero *et al.* 2007, McWilliam *et al.* 2008), with possibly an additional component formed with a time delay of a few Gyr (e.g. Tsujimoto & Bekki 2012, Grieco *et al.* 2012), while pseudo-bulges/bars evolve from a buckling instability over longer timescales.

However, very recently, it has been proposed that pseudo-bulges of massive spiral galaxies could form at high redshift, via a combination of disk instabilities and tidal interactions or mergers, on dynamical timescales rather than through secular processes (Guedes *et al.* 2013). Such a model agrees with the old age and the alpha and r-process element enhancement of the dominant bulge stellar population.

Despite the many efforts in the recent years to build up sizable samples of stars for which both chemical abundances and radial velocities are known with great accuracy, the massive and systematic exploration of the bulge stellar populations is still in its infancy, and this is especially the case for the inner bulge.

A number of surveys using medium-high resolution optical spectroscopy are ongoing at the VLT (e.g. the Gaia-ESO Survey) and at the AAT (the HERMES survey) which are mostly observing the outer bulge regions where extinction is not prohibitive. Only APOGEE is surveying the bulge in the near infrared, but because of the small size of the telescope only the brightest giants near the red giant branch tip can be measured.

In the coming era of Gaia, VISTA and LSST projects, which will provide accurate photometry and proper motions of huge samples of stars in the whole Galaxy, it will be of primary importance to have follow-up facilities to measure the star detailed chemical composition and radial velocities, and precisely reconstruct the Milky Way structure and its overall formation and evolutionary history.

In order to fulfill this goal, efficient spectrographs with large multiplexing capabilities and covering a spectral range as wide as possible from the optical to the near infrared, are definitely urgent.

In this respect, two new projects, namely MOONS for the VLT (e.g. Cirasuolo *et al.* 2012 and 4MOST for VISTA (e.g. de Jong *et al.* 2012), which have recently passed ESO Phase A reviews, are especially suited for the study of the disk and bulge populations.

MOONS is a near-infrared multi-object spectrograph with 1,000 fibers, full spectral coverage between the Ca triplet region and the H band at a spectral resolution R=4,000-8,000, with also the possibility of using higher resolution (R 20,000) gratings to observe in the J and H bands. This instrument will be unique to characterize the kinematics and chemistry of statistical significant samples of red clump and bright giant stars in the inner bulge and disk and in the Galactic center region, where extinction is severe.

4MOST is a fiber-fed optical spectrograph working at low-medium resolution, with a huge (a few 10^3) multiplexing and a large (a few degrees) field of view. This facility will be somewhat complementary to MOONS and it will be very powerful to measure huge numbers of stars in the outer bulge and disk.

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Discussion

Wang: In consideration of the chemical abundances of Galactic Bulge, I would like to recall you a work done by Wang & Liu (2007) who measured the chemical abundances of Bulge planetary nebulae. The found that Bulge PNe are about 0.1-0.2 dex more metal rich and have 0.2 dex lower [C/O] ratio than disk PNe.

Livia Origlia: Thanks for your comment.