Stellar Populations in the Milky Way and Beyond
Proceedings IAU Symposium No. 395, 2026
J. Meléndez, C. Chiappini, R. Schiavon & M. Trevisan, eds.
doi:10.1017/S1743921325001073

The Galactic bulge

Beatriz Barbuy

Universidade de São Paulo, IAG, Rua o Matão 1226, Cidade Universitária, São Paulo 05508-900, Brazil

Abstract. The Galactic bulge is an interesting and complex structure that, to be disentangled, needs photometric, spectroscopic, and astrometric observations of bulge field and globular cluster stars, as well as dynamical calculations. The progress in these directions in the last years is allowing us to better decipher the early formation and chemical evolution of the Galaxy. In the present text we describe in general lines the different aspects of studies on the formation of the bulge, the age and metallicity of stars and globular clusters, effects of the bar and finally available abundances and their chemical evolution.

Keywords. globular clusters, Galaxy: bulge

1. Introduction

The Galactic bulge is the most complex structure in the Galaxy, including probably its oldest stars, and at the same time having being enriched very rapidly by supernovae type II (e.g. Matteucci 2021). It contains as well stellar populations of the inner halo, inner thin and thick disks, and stellar populations transferred from the disk to the bulge by the bar, besides accreted former dwarf galaxies.

The studies on the bulge were intensified after the 8m telescopes made available high signal-to-noise and high spectral resolution data, in the 2000s. The studies were greatly helped with the advent of Gaia that permitted to distinghish structures being accreted, from their coincident proper motions (Gaia Collaboration: Brown et al. 2021). James Webb Space Telescope (JWST) is already bringing new data, and in the near future upcoming facilities such as MOONS@VLT, LSST, and the gigantic telescopes, NASA and ESA satellites (Roman, etc.) among others, will improve our knowledge on the Galactic bulge. These evidences, together with observations of distant galaxies in formation, and numerical simulations, will boost the field of galaxy formation to new views.

In this paper we describe in Section 2 breakthroughs in the progressive exploration of the Galactic bulge, until around 2020. In Sect. 3 are described the main lines of bulge formation and in Sect. 4 the accretion of structures revealed with the help of Gaia proper motions. In Sect. 5 the globular clusters in the Galactic bulge are described and the oldest in situ globular clusters are highlighted as the earliest objects in the Galaxy. In Sect. 6 the formation of the bar is briefly discussed. In Sect. 7 abundances and chemical evolution models are briefly revised. Finally, conclusions are drawn in Sect. 8 and a few challenges for the future are listed in Sect. 9.

2. History along our lifetime

The first observation of the Galactic bulge was presented by Baade (1944a). He observed in the direction of NGC 6522, and obtained the corresponding Colour-Magnitude Diagram (CMD) different from young populations, that led him to the designation of Population II for that CMD. Baade's conclusion was that the nuclear

© The Author(s), 2026. Published by Cambridge University Press on behalf of The International Astronomical Union.

https://doi.org/10.1017/S1743921325001073 Published online by Cambridge University Press

bulge of the Galaxy consisted of a globular cluster-like stellar population. Later, Nassau & Blanco (1958) and Van den Bergh (1972) observed other parts of the bulge and concluded that the bulge is dominated by metal-rich M stars. In the following, we describe results that appear to us as the main breakthrough discoveries since then:

• Eleven years later, Whitford & Rich (1983) obtained spectra of bulge stars, showing that it contained very metal-rich stars (see their Figure 1).

• Another 11 years later McWilliam and Rich (1994) presented the first high-resolution abundances that resulted in metallicities in the range $-1.0 <$ [Fe/H] $< +0.45$.

• The first study of bulge globular clusters (GCs) was carried out by Bica & Alloin (1986) that published a library of integrated spectra of star clusters: to accomplish these observations the slit was set in the east-west direction, and the telescope was moved back and forth in the N-S direction, thus scanning in delta; the reduced spectra were then added in alpha. Bica (1988) showed that the spectra of metal-rich clusters were very similar to spectra of ellipticals and bulges of spirals. This allowed the identification of the most metal-rich clusters that are found in the Galactic bulge, such as NGC 6528, NGC 6553, and Liller 1.

• Minniti (1995) showed that the inner metal-rich clusters appeared to be kinematically associated with the bulge.

• Among the first observations with the Hubble Space Telescope (HST), Ortolani et al. (1995) demonstrated that the CMD of the metal-rich clusters NGC 6528 and NGC 6553, indicated them to be as old as the well-known halo/disk cluster 47 Tucanae, and that the bulge is old.

• However, Kiraga et al. (1997) alleged that the bulge field instead would be young.

• Zoccali et al. (2003) used NTT-SOFI and NICMOS@HST observations demonstrating the similarity between the bulge field and NGC 6528, therefore that the bulge field is also old.

• Clarkson et al. (2008) confirmed the old age of the bulge based on 4 bulge fields observed with the HST.

• A new challenge was launched by Bensby et al. (2017), by observing 90 microlensed stars, in principle located at the distance of the bulge, among which about 15% of them would be younger than 8 Gyr. Stars at a metallicitiy peak at [Fe/H]~ -1 should be old, but for progressively higher metallicities the ages would be progressively younger. Bensby et al. (2017) used the Y2 Demarque et al. (2004) isochrones, with helium abundance Y=0.29.

• Renzini et al. (2018) inspected the same four windows as Clarkson et al., by distinguishing the metal-poor from the metal-rich field stars, and overplotting isochrones with helium abundances of Y=0.29 and 0.33: the difference is small. But could helium be higher? Up to now, we do not know the helium abundance of very metal-rich stars. There are also uncertainties on the mixing-length parameter on stellar evolution models that could affect the age (Li et al. 2024), as pointed out by Renzini in this meeting.

• Finally, in the 2010's several spectroscopic surveys have shown several metallicity peaks in the bulge field. Babusiaux et al. (2010) found peaks at [Fe/H] $= -1.09, -0.27, +0.14$ correlated with velocity dispersions of 127±26, 83±5 and 70±6. Hill et al. (2011) observed red clump giants and found peaks at [Fe/H] $= -0.30$ and $+0.32$, and a smaller proportion of low metallicity stars extending to [Fe/H] $= -1.1$. This was followed by the ARGOS survey by Ness et al. (2013) and the GIBs survey by Zoccali et al. (2017), besides the Gaia-ESO (GES) survey (Schultheis et al. 2017) with rather similar metallicity peaks. Rojas-Arriagada et al. (2020) compared the APOGEE metallicity distributions vs. all these surveys, and found peaks at [Fe/H] $= -0.66, -0.17$, and $+0.32$ dex.

• In this list of impacting discoveries related to the Galactic bulge, we cannot not cite the Apache Point Observatory Galactic Evolution Experiment (APOGEE project -

https://doi.org/10.1017/S1743921325001073 Published online by Cambridge University Press

Majewski et al. (2017), that carried out observations in the H-band of $7{\times}10^5$ stars in the Milky Way, with a good part of them in the bulge. Many of the APOGEE results are impacting studies of the inner Galaxy (e.g. Schiavon et al. 2017; Queiroz et al. 2020, Queiroz et al. 2021; Fernández-Trincado et al. 2022), among many others.

3. Formation of the Galactic bulge

The Large Scale Structure calculations (e.g. Angulo et al. 2012) show that, within filaments, the first structures appeared, with proto-galaxies forming in the core of dark matter haloes, that themselves merged progressively in the early Universe (White & Rees 1978; Gao et al. 2010; Renaud et al. 2017). An early bulge containing baryonic matter then accreted or merged with other such unities and grows (e.g. Pillepich, Madau & Mayer 2015). This could be called the early bulge, where already the first stars and globular clusters form.

For the sequence of events, before the bar formation, there are several simulations that can be accomodated in two kinds of hypotheses. The first consists in forming the bulge (and thick disk) very early via strong gas accretion (Tacchella et al. 2016, Dekel & Burkert 2014. The disk, fed by cold streams, undergo violent disk instability that drives gas into the center, along with mergers. Spheroidal star-forming systems, called blue nuggets, undergo compactation, and then being quenched, are called red nuggets, that will become low-z spheroids.

A second kind of model involves clumps that migrate to the center of early disk galaxies (Noguchi 1999; Immeli et al. 2004; Bournaud et al. 2009; Mandelker et al. 2016).

Finally, the secular evolution scenario, based on the presence of a bar, suggests the formation of the bulge from the disk, through bar instability (Combes et al. 1990, Kormendy & Kennicutt 2004, Shen et al. 2010, Debattista et al. 2017). This reasoning was strenghtened with the BRAVA survey (Rich et al. 2007), that measured a cylindrical rotation of the bulge. Essentially, bar instability and bucling instability are the cause of a two-step heating, and the radial gradient is transformed into a vertical gradient.

As a conclusion, we can say that certainly the early structure has been formed and that, later on, the bar formed. Processes in between are still uncertain, but it could well be that all these processes took place.

4. Accretion of dwarf galaxies

In addition, in particular since the advent of the Gaia proper motion measurements (Gaia Collaboration: Brown et al. 2021; Gaia Collaboration: Vallenari et al. 2023), accreted structures were identified. Suggested structures found to be mixed within the Galactic bulge stellar populations are Heracles (Horta et al. 2021), Kraken (Kruijssen et al. 2020), Koala (Forbes 2020), Aurora (Myeong et al. 2022; Belokurov & Kravtsov 2023), and a smaller contribution from Gaia-Enceladus-Sausage (Belokurov et al. 2018; Helmi et al. 2018). Heracles in particular is very similar to the identified early bulge, in terms of abundances and energy, with one difference being that Heracles is Al-deficient.

The GCs located in the inner Galaxy, listed by (Bica et al. 2016, 2024) are tracers of early bulge vs. the accreted structures. Age-metallicity relations (AMR) show two sequences of GCs, one with old ages > 12 Gyr, classified as formed in situ, and the other, with ages from 6 to 14 Gyr that should have formed ex-situ and brought to the Galaxy via their accreted progenitor structures. This is clearly shown in Forbes & Bridges 2010, Forbes 2020, Massari et al. 2019, Kruijssen et al. 2020, Callingham et al. 2022, Bica et al. 2024, Belokurov & Kravtsov 2024.

https://doi.org/10.1017/S1743921325001073 Published online by Cambridge University Press

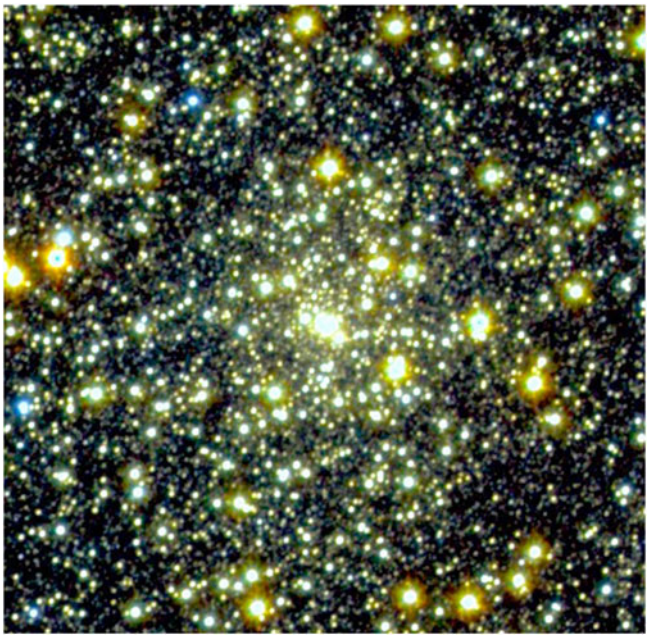


Figure 1. JHK$_s$-combined colour image from the VVV survey. The image has a size of 2×2 arcmin^2. North is at 45° clockwise. Reproduced from Barbuy et al. (2016).

5. Globular clusters: fossils of the Galactic bulge

In Figure 1 we reproduce a VVV image of HP 1, with an age of $12.8^{+0.9}_{-0.8}$ Gyr (Kerber et al. 2019), and metallicity [Fe/H]=−1.06±0.10 (Barbuy et al. 2016), that we suggest to be a fossil relic of the Galactic bulge.

Bica et al. (2016) catalogued 43 bulge globular clusters. With recent observations, mostly from surveys in the near-infrared (JHK) VVV and VVVX (Minniti et al. 2010, Saito et al. 2024, and the mid-infraed WISE mission (Wright et al. 2010) operating in bands 3.4, 4.6, 12, and 22 μm, many new clusters were revealed. Bica et al. (2024) updated list of bulge clusters amounts to 61 of them, with all the 43 more well-known clusters confirmed to have formed in situ. As for the new clusters only a few radial velocities are available so far, and their origin is still uncertain. Here we note a similar paper by Garro et al. (2024). In Bica et al. (2024) we see two metallicity peaks of bulge clusters, at [Fe/H] ≈ −1.1 and −0.5. Note that among metal-poor field stars, most of them have [Fe/H] ∼ −1, and moreover most of the very metal-poor stars in the bulge should be halo stars (Lucey et al. 2021, 2022).

The newly discovered clusters are low-mass, and some of them are clearly ex-situ accreted ones. One example of an interesting ex-situ GC is VVV-CL001 (Minniti et al. 2011). It has a radial velocity of −326 km/s, E(B-V)=2.20 and [Fe/H]=−2.45. It is the most metal-poor GC in the Galaxy (another one is the halo GC ESO280-SC06, [Fe/H]=−2.45). Fernández-Trincado et al. (2021) obtained from Gemini/IGRINS spectra metallicities of [Fe/H]=−2.4 and −2.1 (11 stars) for VVV-CL001. Both these GCs are possibly associated with Gaia-Enceladus-Sausage, or Sequoia accreted structures.

The age-metallicity relation of the very old moderately metal-poor clusters indicates that their star formation rate took place 10 times faster than the star formation rate in clusters accreted from dwarf galaxies (see Fig. 10 in Souza et al. 2024).

For the classification of GCs as in situ or ex-situ, the main uncertainty is the distance, even in the Gaia era. One example is Palomar 6, for which Souza et al. (2021) used HST

https://doi.org/10.1017/S1743921325001073 Published online by Cambridge University Press

CMDs deriving $d_{\odot}$=7.67±0.19 kpc, placing it in the bulge, in contrast to $d_{\odot}$=5.8 kpc from Harris (1996, updated in 2010), and adopted by Baumgardt et al. (2019). Another example is NGC 6558, for which Souza et al. (2024) derived $d_{\odot}$=8.5 kpc, from simultaneous fitting of HST optical and GSAOI@GEMINI near-infrared CMDs, contrasted with $d_{\odot}$=7.47 kpc by Baumgardt & Vasiliev (2021).

Finally, integrals of motion and Energy vs. angular momentum L_Z are also indicators of in situ vs. ex situ origin of clusters, with the in situ ones having the lowest energies.

6. The bar

An important issue is the time of bar formation, that can be a discriminant among dominant processes in the bulge, before the bar formation itself.

The available estimations are that the bar formed 8±2 Gyr ago by Buck et al. (2018(@), ∼8 Gyr ago by Bovy et al. (2018), ∼3 Gyr ago by Nepal et al. (2024), and ∼8-11 Gyr ago, based on Mira variables in the Nuclear stellar disk by Sanders et al. (2024).

Pérez-Villegas et al. (2020) computed the orbits of GCs and concluded that many of them are trapped by the bar. On the other hand, Most of them are not supporting the bar structure, and 7 clusters that are supporting the bar, do not necessarily support the X-shape. This leads to the supposition that the bulge GCs formed much before the bar, and that if they are in the bar, this is due to having been trapped when the bar formed.

7. Abundances and chemical evolution models

High-resolution spectroscopy of bulge red giants require 8m telescopes, and therefore there are not many of them. We refer the reader to Barbuy et al. (2018, 2023, 2024), where a number of such papers are cited. Here we would like to note the work by Nissen & Schuster (2010) and Nissen et al. (2024), showing that not only the alpha-elements can distinguish between in situ and ex situ stars, but also Na and iron-peak elements, i.e., they are enhanced in in situ stars, and with a solar-like ratio in ex situ stars. This is due to the fast chemical enrichment of the Galactic bulge, dominated by supernovae type II, whereas in low mass dwarf galaxies the chemical evolution is much slower, giving time to enrichment by supernovae type Ia (e.g. Matteucci 2021). The fast chemical enrichment of the bulge is similar to that of ellipticals and other bulges of spirals (Matteucci & Brocato 1990).

A major work on chemical evolution models of the bulge, along the years, is described in Matteucci (2021, and references therein). We have been developing models based on the early work on ellipticals by Friaça & Terlevich (1998), consisting in a multi-zone chemical evolution coupled with a hydrodynamical code. For the Galactic bulge, a classical spheroid with a baryonic mass of 2×10^9 $M_{\odot}$ and a dark halo mass of 1.32×10^{10} $M_{\odot}$ are assumed (e.g. Friaça & Barbuy 2017). Models fit well the data for all studied elements, with a fast specific star formation rate of 1 Gyr^{-1} as shown in the papers cited above in this section.

An interesting example is shown in Figure 2, with abundances of Cobalt and Copper in bulge stars. As suggested by S.E. Woosley (private communication), the abundance derivation of these elements are of interest to elucidate their origin as neutron capture elements on iron-group nuclei during He burning and later burning stages, also called the weak-s component (Limongi & Chieffi 2003), and the α-rich freeze-out in the deepest layers (Woosley & Weaver 1995 (WW95); Sukhbold et al. 2016). The higher curves for Co follow a suggestion by Timmes et al. (1995), that the yields of Co from WW95 multiplied by two would satisfy better the observed values. We see however with the new Co abundances for moderately metal-poor stars by Barbuy et al. (2024) that the original yields fit better the new data. In summary, we conclude that both Co and Cu tend do

https://doi.org/10.1017/S1743921325001073 Published online by Cambridge University Press

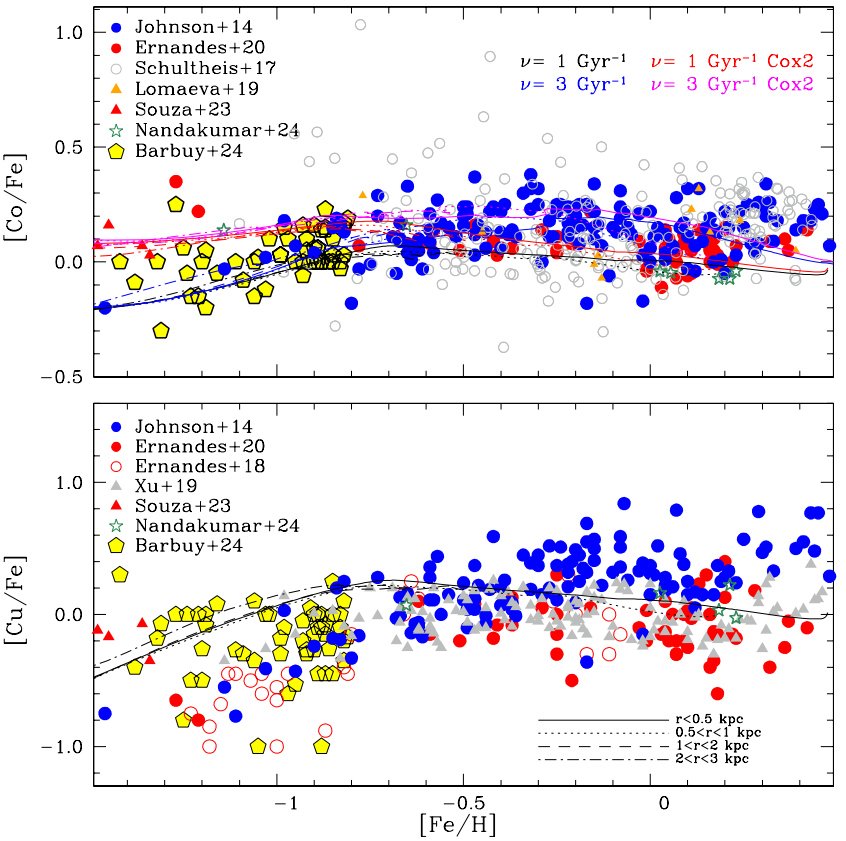


Figure 2. [Co/Fe] vs. [Fe/H] (upper panel) and [Cu/Fe] vs. [Fe/H] (lower panel): Chemical-evolution models with specific star formation of $\nu = 1$ and 3 Gyr $^{-1}$ for original yields from Woosley & Weaver (black and blue respectively), and for Co yields multiplied by two (red and magenta lines). Data consist of the results from Barbuy et al. (2024) (yellow pentagons) and literature data, including field data from Johnson et al. (2014) (blue filled circles), Ernandes et al. (2020) (red filled circles), Lomaeva et al. (2024) (orange filled triangles), Nandakumar et al. (2024) (blue open stars), Schultheis et al. (2017) (open grey circles), and Xu et al. (2019) (filled grey triangles), plus GC data from Ernandes et al. (2018) (red open circles) and Souza et al. (2023) (red filled triangles). Different model lines correspond to different radii from the Galactic centre. Adapted from Barbuy et al. (2024).

show a secondary behaviour, therefore appearing to be more dominantly produced rather by a weak s-process than by alpha-rich freeze-out. Further data are needed for a more firm conclusion in this respect.

Another puzzling result is the several very Na-rich stars, in particular around solar metallicity seen in Figure 4 by Barbuy et al. (2023), and also seen in Figure 2 by Smiljanic et al. (2016). Abundance variations of C and N in globular clusters were known since the 1970s (e.g. Osborn 1971). It is now known that variations in C, N, O, Na, Al, as well as in Mg, Si, and K are detected. In particular stars with high N and Na, and low C and O, and Mg-Al anticorrelations were described in Gratton et al. (2004), Carretta et al. (2009) for example. The connection with multiple stellar populations is now clear, as demonstrated in Piotto et al. (2015) - see reviews by Gratton et al. (2012) and Milone & Marino (2022).

The Na excess that we find in some field bulge stars, that stand out of the mean distribution, ranges from [Na/Fe] $\sim +0.3$ up to $+1.0$. In conclusion, this could well be

https://doi.org/10.1017/S1743921325001073 Published online by Cambridge University Press

due to these stars having their origin as second generation stars evaporated from globular clusters.

8. Conclusions

Here are some conclusions:

• The Bulge formation is probably a mix of scenarios, including a) an early hierarchical merging of dark matter halos, b) a subsequent very early bulge forming already the oldest bulge globular clusters, with a possibly concomitant disk formation via winds and/or clumps, and finally d) the bar formation that took place later on, transforming it to an X-shape (or box/peanut shape), and trappping most of its stars.

• The bulge stellar populations include a mix of an early spheroid, inner thin and thick disk, inner halo, plus accreted structures and the bar that brings together disk stars and gas (Queiroz et al. 2020, Queiroz et al. 2021).

• CMDs of several windows in the bulge indicate that is is old, but a fraction of younger stars is possible among the most metal-rich stars. However for metal-rich stars the helium abundance is not known, which could change their deduced ages.

• The moderately metal-poor and blue horizontal branch bulge GCs are old: 12.3 to 13.5 Gyr (Souza et al. 2024), and formed in situ very early in the Galaxy life. They are later trapped by the bar (Pérez-Villegas et al. 2020). As for a possibility of these GCs to have been formed in the bar, this is only possible if the bar formed very early, but there is no evidence for that.

• The abundances of alpha-elements: Mg, Si, Ti (not Ca), Na, and iron-peak elements: Sc, V, Mn, Co, Ni, Cu, Zn (not Cr) can indicate in-situ or ex-situ origin, being enhanced in in-situ originated stars, and low in ex-situ originated stars (Nissen & Schuster 2010; Nissen et al. 2024).

• Chemical Evolution models with a fast star formation rate of 1 Gyr do reproduce the observed abundances of all studied elements.

9. Challenges

• Are there young stars in the bulge in a significant fraction? Measurements of He abundances in metal-rich stars are not available. If He abundance would be higher than Y$\sim$0.33 it would affect the age derivation, in the sense of making the stars older. Mixing-length parameters adopted in models also make the ages of the most metal-rich stars to be uncertain.

• High-resolution spectroscopy of turn-off stars (and subgiants) in globular clusters would be of great interest, in particular for Lithium studies. Crowding will be a difficult practical problem for such observations with the gigantic telescopes of the near future.

• Most primitive stars in the proto-Milky Way are the most metal-poor ones? or in fact the bulge moderately metal-poor ones, that reached metallicities of [Fe/H]~-1 due to a fast chemical enrichment in the bulge, would be the oldest ones ?

• There are different views in the literature about what is inner halo and what is bulge.

• Which are the more important mechanisms that formed the bulge, before bar formation? The conclusions given in Barbuy et al. (2018) concerning the early bulge formation still holds: "we do not yet have a fully self-consistent chemodynamical bulge model in the cosmological frame-work, and we will also need more extensive chrono-chemical-kinematic 3D map of stars to better constrain such models."

• What exactly is the early bulge, identified by a fast chemical enrichment of around 1 Gyr? Is Heracles part of the early bulge or an accreted structure ?

https://doi.org/10.1017/S1743921325001073 Published online by Cambridge University Press

Acknowledgements

I am very grateful to my former students that, together with Cristina Chiappini, organized this event, and dedicated this effort to hounour my career. In particular Jorge Meléndez that, together with Cristina Chiappini, led the IAU proposal, acted as SOC-chairs, and bringing the support of the IAG-USP staff. I also thank the IAG-USP director, Ricardo Trindade, for the logistical support. Thanks to Bruno Castilho, together with Paula Coelho, that led the LOC organization, bringing the support and great help of the Laboratório Nacional de Astrofísica (LNA/MCTI) staff. I also thank the LNA/MCTI director Wagner Corradi for the logistical support. Simone Daflon from Observatório Nacional (ON/MCTI) was also very proactive in organizing logistics from Rio de Janeiro. I also thank the director of ON/MCTI Jailson Souza de Alcaniz. I also thank my former students Bruno Dias (SOC member), Marina Trevisan (SOC member), Paula Coelho (LOC-co-organizer), Ricardo Schiavon, Rodolfo Smiljanic that co-organized the event, and Silvia Rossi, Heitor Ernandes, Raphael de Oliveira, Stefano de Souza, André Milone that attended the event. Also Alan Alves-Brito was a LOC co-organizer but could not attend.

We are all thankful to the SOC and LOC members, and to many collaborators and friends that attended the meeting.

I am also grateful to Alvio Renzini, to have accepted to present the meeting conclusions, and thus as a follow-up of the IAU Symposium entitled The Stellar Populations of Galaxies, that took place in 1991 in Angra dos Reis, near Paraty - see Proceedings of the 149th Symposium of the International Astronomical Union, held in Angra dos Reis, Brazil, August 5-9, 1991. Edited by Beatriz Barbuy and Alvio Renzini. International Astronomical Union. Symposium no. 149, Kluwer Academic Publishers, Dordrecht, 1992.

Finally I thank the IAU for approving this meeting. As a previous Committee 29, and Division IV President, and Vice-President of the IAU, I recognize that the IAU meetings are a most important sponsorship of the Union. Indeed it is rare to have other meetings with as many participants and coming from so many countries.

References

Angulo, R.E., Springel, V., White, S.D.M. et al. 2012, MNRAS, 426, 2046.
Baade, W. 1944a, ApJ, 100, 137.
Baade, W. 1944b, ApJ, 100, 147.
Babusiaux, C., Gómez, A., Hill, V. et al. 2010, A&A, 519, 77.
Barbuy, B., Cantelli, E., Vemado, A. et al. 2016, A&A, 591, A53.
Barbuy, B., Chiappini, C., Gerhard, O. 2018, ARA&A, 56, 223.
Barbuy, B., Friaça, A.C.S., Ernandes, H. et al. 2023, MNRAS, 526, 2365.
Barbuy, B., Friaça, A. C. S., Ernandes, H., et al. 2024, A&A, 691, A296.
Baumgardt, H., Hilker, M., Sollima, A., Bellini, A. 2019, MNRAS, 482, 5138.
Baumgardt, H., & Vasiliev, E. 2021, MNRAS, 505, 5957.
Belokurov, V., Erkal, D., Evans, N. W., Koposov, S. E., Deason, A. J. 2018, MNRAS, 478, 611.
Belokurov, V., & Kravtsov, A. 2023, MNRAS, 525, 4456.
Belokurov, V., & Kravtsov, A. 2024, MNRAS, 528, 3198.
Bensby, T., Feltzing, S., Gould, A. et al. 2017, A&A, 605, 89.
Bica, E., Alloin, D. 1986, A&A, 162, 21.
Bica, E. 1988, A&A, 195, 76.
Bica, E., Ortolani, S., Barbuy, B. 2016, PASA, 33, 28.
Bica, E., Ortolani, S., Barbuy, B., Oliveira, R.A.P. 2024, A&A, 687, A201.
Bournaud, F., Elmegreen, B.G., Martig, M. 2009, ApJ, 707, L1.
Bovy, J., Kawata, D., Hunt, J.A.S. 2018, MNRAS, 473, 2288.
Buck, T., Ness, M., Macciò, A. et al. 2018, ApJ, 861, 88.

https://doi.org/10.1017/S1743921325001073 Published online by Cambridge University Press

Callingham, T. M., Cautun, M., Deason, A. J., et al. 2022, MNRAS, 513, 4107.
Carretta, E., Bragaglia, A., Gratton, R., Lucatello, S. 2009, A&A, 505, 139.
Clarkson, W., Sahu, K., Anderson, J., et al. 2008, ApJ, 684, 1110.
Combes, F., Debbasch, F., Friedli, D., Pfenniger, D. 1990, A&A, 233, 82.
Debattista, V.P., Ness, M., Gonzalez, O.A. et al. 2017, MNRAS, 469, 1587.
Dekel, A., Burkert, A. 2014, MNRAS, 438, 1870.
Demarque, P., Woo, J.-H. Kim, Y.-C., Yi, S.K. 2004, ApJS, 155, 667.
Ernandes, H., Barbuy, B., Alves-Brito, A., et al. 2018, A&A, 616, A18.
Ernandes, H., Barbuy, B., Friaça, A. C. S., et al. 2020, A&A, 640, A89.
Fernández-Trincado, J.G., Minniti, D., Souza, S.O. 2021,ApJ, 908, L42.
Fernández-Trincado, J.G., Beers, T.C., Barbuy, B. et al. 2022, A&A, 663, 126.
Forbes, D. A., & Bridges, T. 2010, MNRAS, 404, 1203.
Forbes, D. A. 2020, MNRAS, 493, 847.
Friaça, A.C.S., & Barbuy, B. 2017, A&A, 598, A121.
Friaça, A.C.S., & Terlevich, R.J. 1998, MNRAS, 298, 399.
Gaia Collaboration EDR3: Brown et al., 2021, A&A, 649, A1.
Gaia Collaboration DR3: Vallenari et al., 2023, A&A, 674, A1.
Gao, L., Theuns, T., Frenk, C.S. et al. 2010, MNRAS, 403, 1283.
Garro, E., Minniti, D., Fernández-Trincado, J.G. 2024, A&A, 687, A214.
Gratton, R.G., Sneden, C., Carretta, E. 2004, ARA&A, 42, 385.
Gratton, R.G., Bragaglia, A., Carretta, E. 2004, A&ARev, 20, 50.
Harris, W.E. 1996, AJ, 112, 1487.
Helmi, A., Babusiaux, C., Koppelman, H. H., et al. 2018, Nature, 563, 85.
Hill, V., Lecureur, A., Gómez, A., et al. 2011, A&A, 534, A80.
Horta, D., Schiavon, R. P., Mackereth, J. T., et al. 2021, MNRAS, 500, 1385.
Immeli, A., Samland, M., Gerhard, O., Westera, P. 2004, A&A, 413, 547.
Johnson, C.I., Rich, R.M., Kobayashi, C., Kunder, A., & Koch, A. 2014, AJ, 148, 67.
Kerber, L.O., Libralato, M., Souza, S.O. et al. 2019, MNRAS, 484, 5530.
Kiraga, M., Paczynski, B., Stanek, K.Z. 1997, ApJ, 485, 611.
Kormendy, J., Kennicutt, Jr. R.C. 2004. ARA&A, 42, 603.
Kruijssen, J. M. D., Pfeffer, J. L., Chevance, M., et al. 2020, MNRAS, 498, 2472.
Li, Y., Bedding, R., Huber, D. et al. 2024, ApJ, 974, 77.
Limongi, M., & Chieffi, A. 2003, ApJ, 592, 404.
Lomaeva, M., Jönsson, H., Ryde, N., Schultheis, M., Thorsbro, B. 2019, A&A, 625, A141.
Lucey, M., Hawkins, K., Ness, M., et al. 2021, MNRAS, 501, 5981.
Lucey, M., Hawkins, K., Ness, M., et al. 2022, MNRAS, 509, 122.
Majewski, S.R., Schiavon, R.P., Frinchaboy, P.M., et al. 2017, AJ, 154, 94.
Mandelker, N., Padnos, D., Dekel, A. et al. 2016, MNRAS, 463, 3921.
Massari, D., Koppelman, H. H., & Helmi, A. 2019, A&A, 630, L4.
Matteucci, F. & Brocato, E. 1990, ApJ, 365, 539.
Matteucci, F. 2021, A&AR, 29, 5.
McWilliam, A., Rich, R.M. 1994, ApJ, 246, 54.
Milone, A.P., Marino, A.F. 2022, Univ, 8, 359.
Minniti, D. 1995, AJ, 110, 1686.
Minniti, D., Lucas, P.W., Emerson, J.P. et al. 2010, NewA, 15, 433.
Minniti, D., Hempel, M., Toledo, I. et al. 2011, A&A, 527, A81.
Myeong, G. C., Belokurov, V., Aguado, D. S., et al. 2022, ApJ, 938, 21.
Nandakumar, G., Ryde, N., Mace, G. et al. 2024, ApJ, 964, 96.
Nassau, J.J., Blanco, V.M. 1958, ApJ, 128, 46.
Ness, M., Freeman, K., Athanassoula, E. et al. 2013, MNRAS, 430, 836.
Nepal, S., Chiappini, C., Guiglion, G. et al. 2024, A&A, 681, L8.
Nissen, P. E., & Schuster, W. J. 2010, A&A, 511, L10.
Nissen, P. E., Amarsi, A. M., Skúladóttir, Á., & Schuster, W. J. 2024, A&A, 682, A116.
Noguchi, M. 1999, ApJ, 514, 77.

https://doi.org/10.1017/S1743921325001073 Published online by Cambridge University Press

Ortolani, S., Renzini, A., Gilmozzi, R. et al. 1995, Nature, 377, 701.
Osborn, W., 1971, Obs, 91, 223.
Pérez-Villegas, A. Barbuy, B., Kerber, L. O., et al. 2020, MNRAS, 491, 3251.
Pillepich, A., Madau, P., Mayer, L. 2015, ApJ, 799, 184.
Piotto, G., Milone, A.P., Bedin, L.R. et al. 2015, AJ, 149, 91.
Queiroz, A. B. A., Anders, F., Chiappini, C., et al. 2020, A&A, 638, A76.
Queiroz, A. B. A., Chiappini, C., Perez-Villegas, A., et al. 2021, A&A, 656, A156.
Renaud, F., Agertz, O., Gieles, M. 2017, MNRAS, 465, 3622.
Renzini, A., Gennaro, M., Zoccali, M., et al. 2018, ApJ, 863, 16.
Rich, R.M., Reitzel, D.B., Howard, C.D. 2007, ApJ, 658, L29.
Rojas-Arriagada A., Zasowski, G., Schultheis, M. et al. 2020, MNRAS, 499, 1037.
Saito, R.K., Hempel, M., Alonso-Garcia, J. et al. 2024, A&A, 689, A148.
Sanders, J.L., Kawata, D., Matsunaga, N. et al. 2024, MNRAS, 530, 2972.
Schiavon, R.P., Zamora, O., Carrera, R. et al. 2017, MNRAS, 465, 501.
Schultheis, M., Rojas-Arriagada, A., García-Pérez A.E. et al. 2017, A&A, 600, A14.
Shen, J., Rich, R.M., Kormendy, J. et al. 2010, ApJ, 720, L72.
Smiljanic, R., Romano, D., Bragaglia, A. et al. 2016, A&A, 589, A115.
Sukhbold, T., Ertl, T., Woosley, S.E., Brown, J.M., Janka, H.T. 2016, ApJ, 821, 38.
Timmes, F.X., Woosley, S.E., Weaver, T.A. 1995, ApJS, 98, 617.
Souza, S.O., Valentini, M., Barbuy, B. 2021, A&A, 656, A78.
Souza, S. O., Ernandes, H., Valentini, M., et al. 2023, A&A, 671, A45.
Souza, S. O., Libralato, M., Nardiello, D., et al. 2024, A&A, 690, A37.
Tacchella, S., Carollo, C.M., Renzini, A. et al. 2015, Science, 348, 314.
Tacchella, S., Dekel, A., Carollo, C.M. et al. 2016, MNRAS, 458, 242.
Van den Bergh, S. 1972, PASP, 84, 306.
White, S.D.M., Rees, M.J. 1978, MNRAS, 183, 341.
Whitford, A.E., Rich, R.M. 1983, ApJ, 274, 723.
Woosley, S.E., Weaver, T.A. 1995, ApJS, 101, 181.
Wright, E.L., Eisenhardt, P.R.M., Mainzer, A.K. 2010, AJ, 140, 1868.
Xu, X. D., Shi, J. R., & Yan, H. L. 2019, ApJ, 875, 142.
Zoccali, M., Renzini, A., Ortolani, S. et al. 2003, A&A, 399, 931.
Zoccali, M., Vasquez, S., Gonzalez, O.A. 2017, A&A, 599, 12.

https://doi.org/10.1017/S1743921325001073 Published online by Cambridge University Press